



# **CIVIL-309: URBAN THERMODYNAMICS**

**Assist. Prof.  
Dolaana Khovalyg**

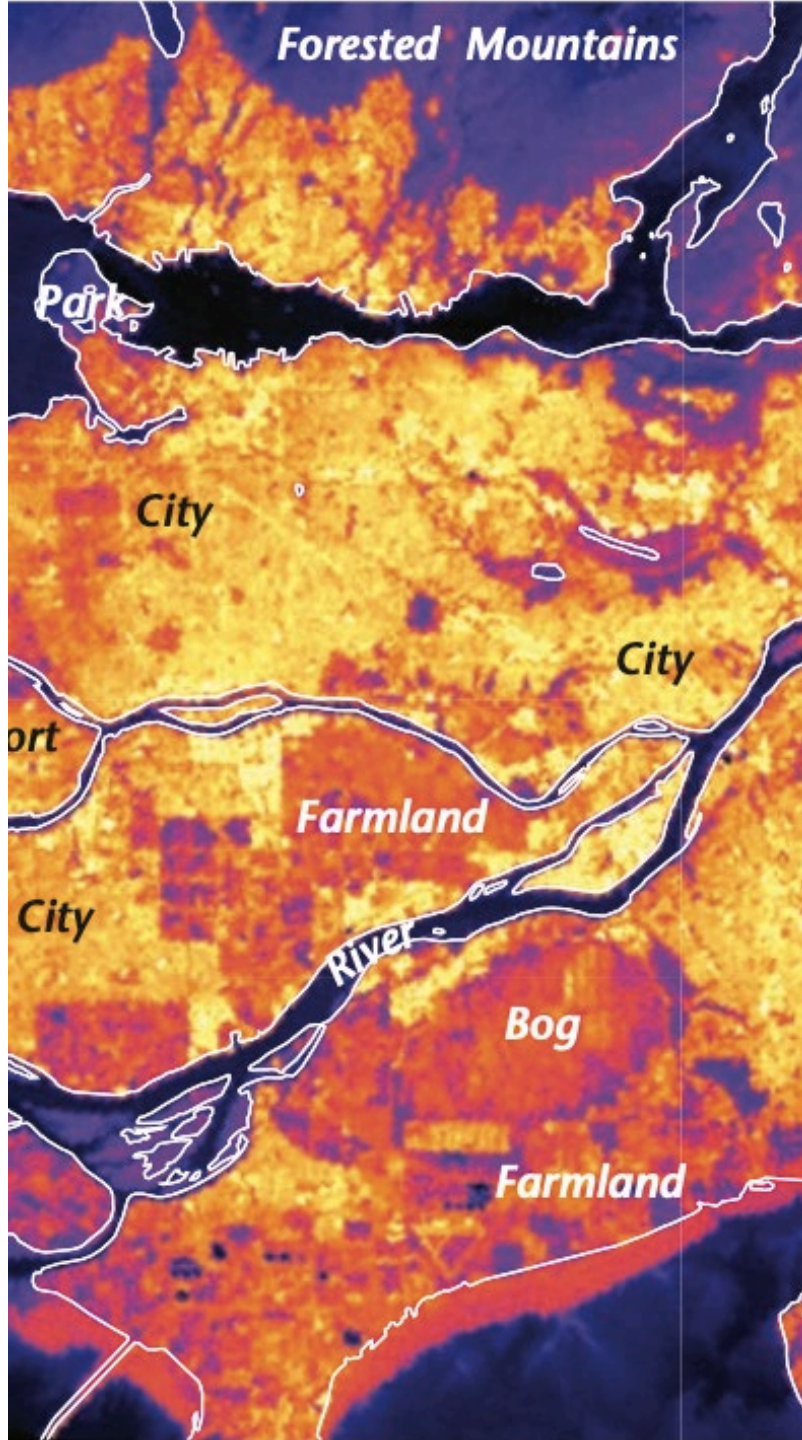
Lecture 06:  
**Buildings-Environment Interaction**

**7 November 2026**

# EPFL Course Schedule



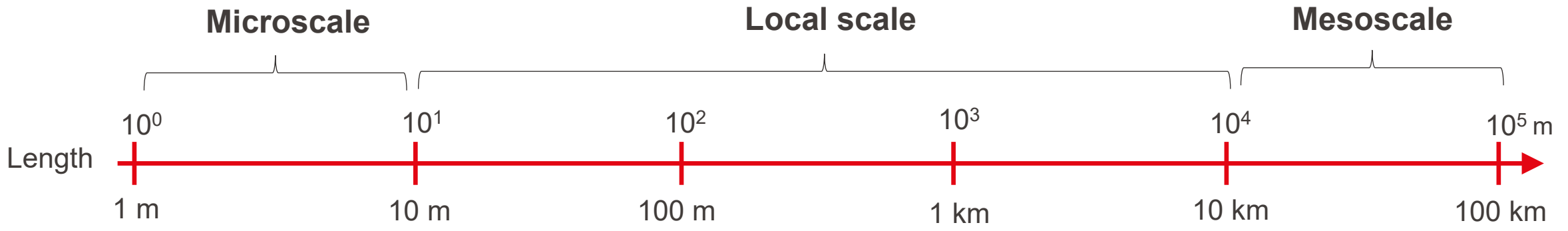
7	24.10		<b>BREAK</b>	
8	31.10	1 x 45'	<b>Urban modeling and computational tools</b>	JY
		1 x 45'	Introduction to the web tool <b>CityTherm</b> (part II)	JY
		1 x 45'	Introduction to the course project II	JY
9	07.11	2 x 45'	<b>Building-environment interaction:</b> thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	<b>Supervised group work - course project II</b>	JY
10	14.11	2 x 45'	<b>Ground-environment interaction:</b> ground properties, thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	<b>Supervised group work - course project II</b>	JY
11	21.11	2 x 45'	<b>Water body - environment interaction:</b> thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	<b>Supervised group work - course project II</b>	JY
12	28.11	2 x 45'	<b>Vegetation – environment interaction:</b> characteristics of vegetation, evapotranspiration, aero- and thermal interaction	DK
		1 x 45'	<b>Supervised group work - course project II</b>	JY
13	05.12	2 x 45'	<b>Human Outdoor Comfort:</b> Parameters affecting human comfort and comfort indices (UTCI, PET)	JY
		1 x 45'	<b>Supervised group work - course project II</b>	JY
14	12.12	1 x 45'	<b>Climate-Sensitive Urban Design:</b> complex interaction of all urban elements and their effect on UHI and outdoor comfort	DK
		2 x 45'	<b>Supervised group work - course project II</b>	JY
15	19.12	3 x 45'	Supervised group work on the course project II <b>Course project II submission deadline: 16:00 on December 19</b>	DK, JY



# CONTENT:

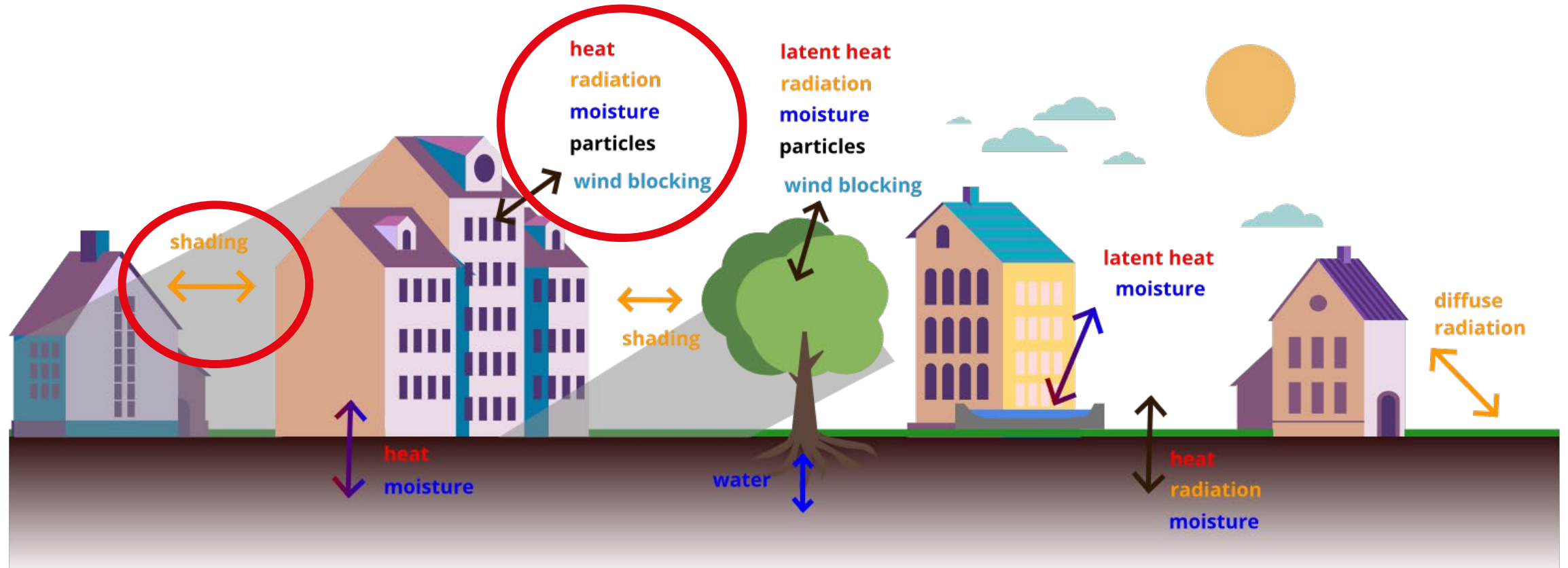
- I. Introduction
- II. Urban energy balance and heat storage
- III. Urban canyon sensible heat exchange
- IV. Urban canyon radiation budget
  - Shortwave vs. Longwave radiation
- V. Aerodynamic interaction
- VI. Hydrodynamic interaction

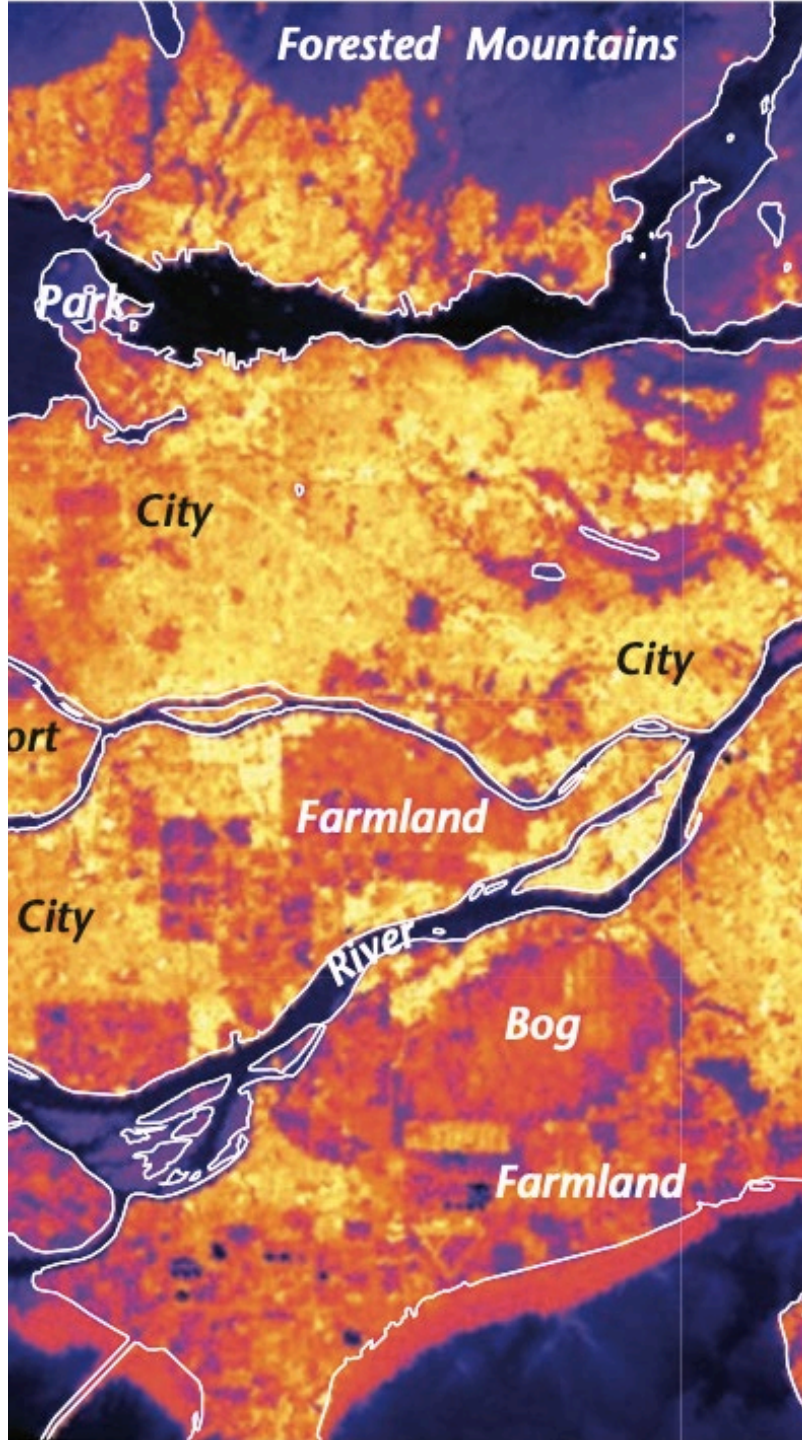
Reminder from L1



# Building-Environment Interaction: Introduction

- Buildings *interact directly* with their surrounding atmosphere by exchanging heat, moisture, and particles.
- Radiation exchange happens with the surrounding urban elements in addition to the Sun.
- Positioning and shapes of buildings affect the wind flow at the neighborhood scale.
- Buildings also *interact* with the ground directly in contact *by exchanging heat and moisture*.





# CONTENT:

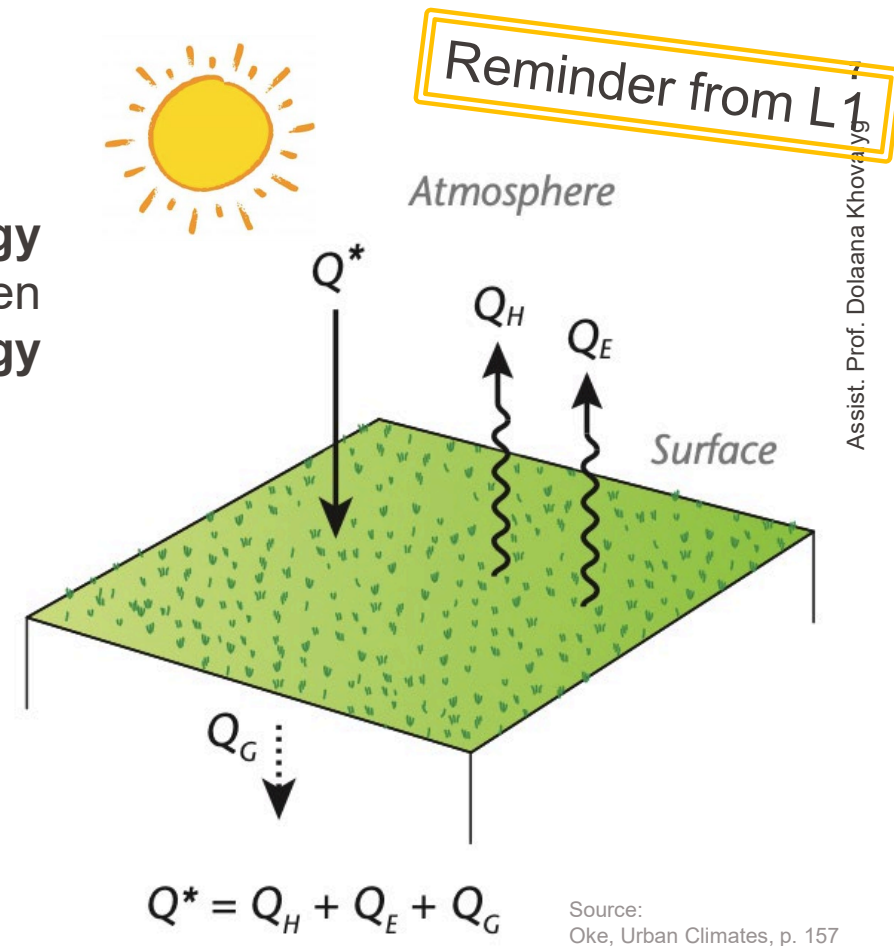
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# EPFL Surface Energy Balance

- The **surface energy balance (SEB)** - the net result of energy exchanges by *radiation*, *convection* and *conduction* between a **surface element** and the **atmosphere**. Due to **energy conservation**, the surface *should always be* at balance.
- **SEB formulation:**

$$(1-2) \quad Q^* = Q_H + Q_E + Q_G \quad (W/m^2)$$

$Q^*$ : Net allwave radiation heat flux  
 $Q_H$ : Sensible heat flux  
 $Q_E$ : Latent heat flux  
 $Q_G$ : Ground heat flux (conduction to the soil)



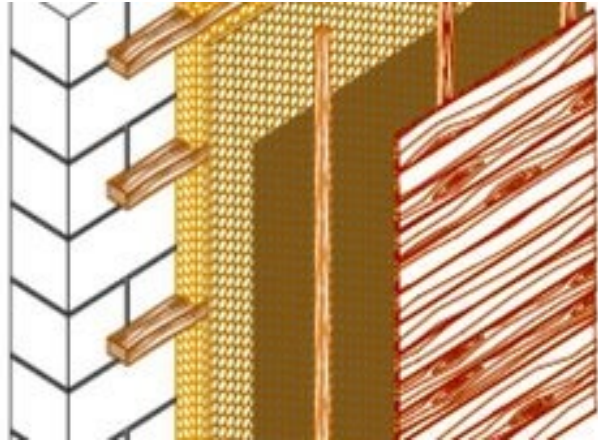
\* the balance in Eqn. (1-2) *simplified* by considering only *vertical fluxes* over the surface

- The **daily** and **seasonal pattern** of the **SEB** is **set** by the **radiation heat flux  $Q^*$**  received from the Sun:
  - During day,  $Q^* > 0$  and energy goes into the soil as sensible heat or into the air through convection.
  - During night,  $Q^* < 0$  and energy is released from surfaces.

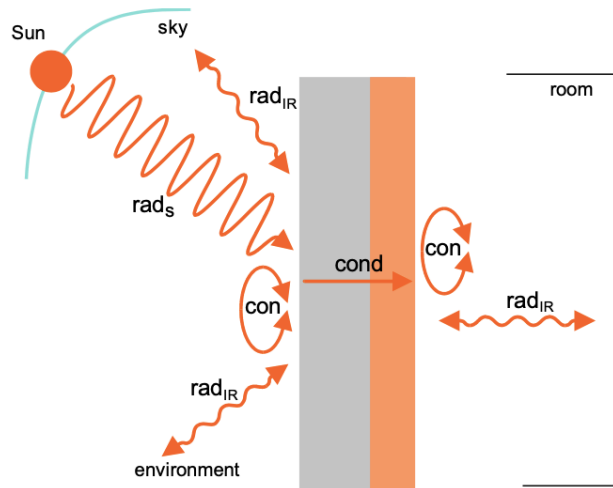
Note that in Oke's book "*Urban Climates*" the **net heat flux** in units of  $W/m^2$  is labeled as [ $Q$ ] (capitalized), while in other sources it could be labeled as [ $\dot{q}$ ] (e.g., in Medved's book)

# EPFL Heat Exchange Across the Building Envelope

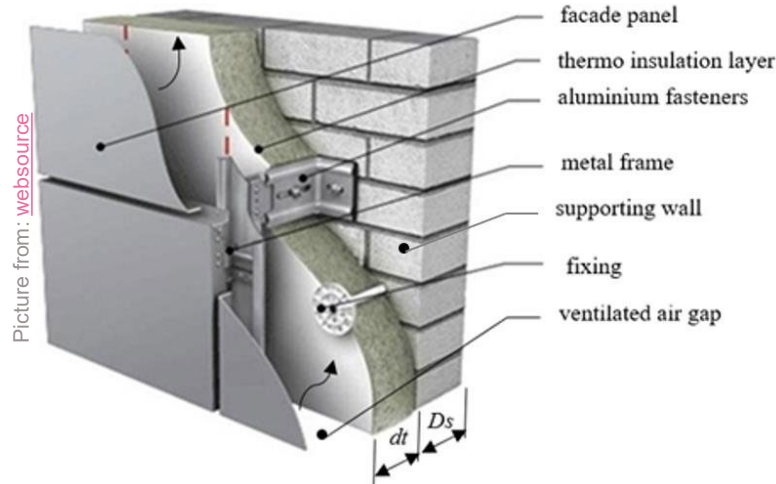
## Plain wall:



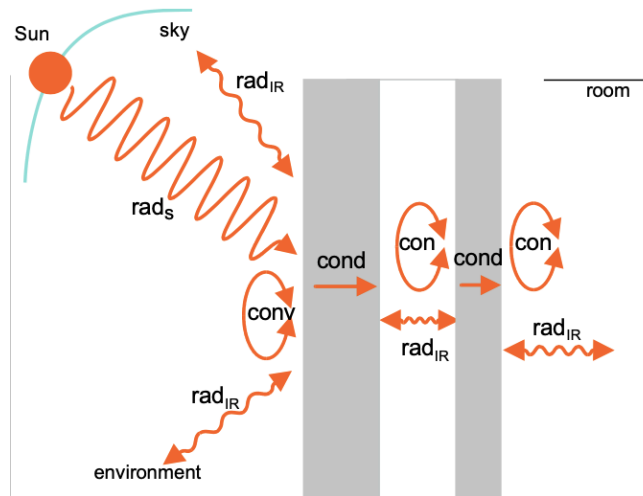
Picture from: [webservice](#)



## Wall with air gap / cavity:



Picture from: [webservice](#)

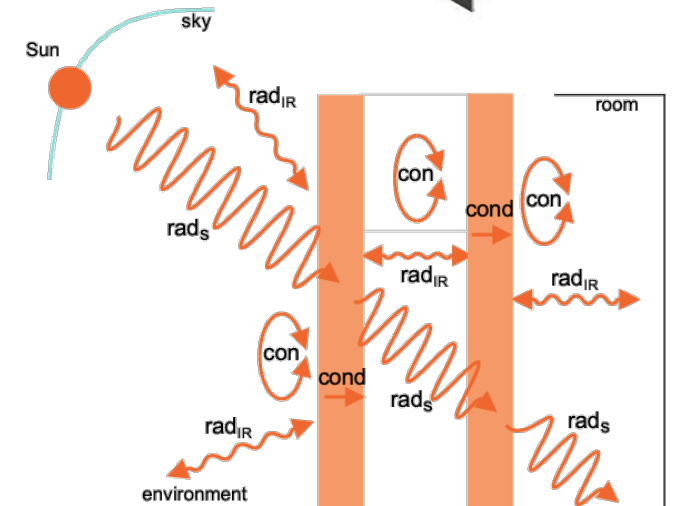


Closed air gap illustration

## Glazed element (window):



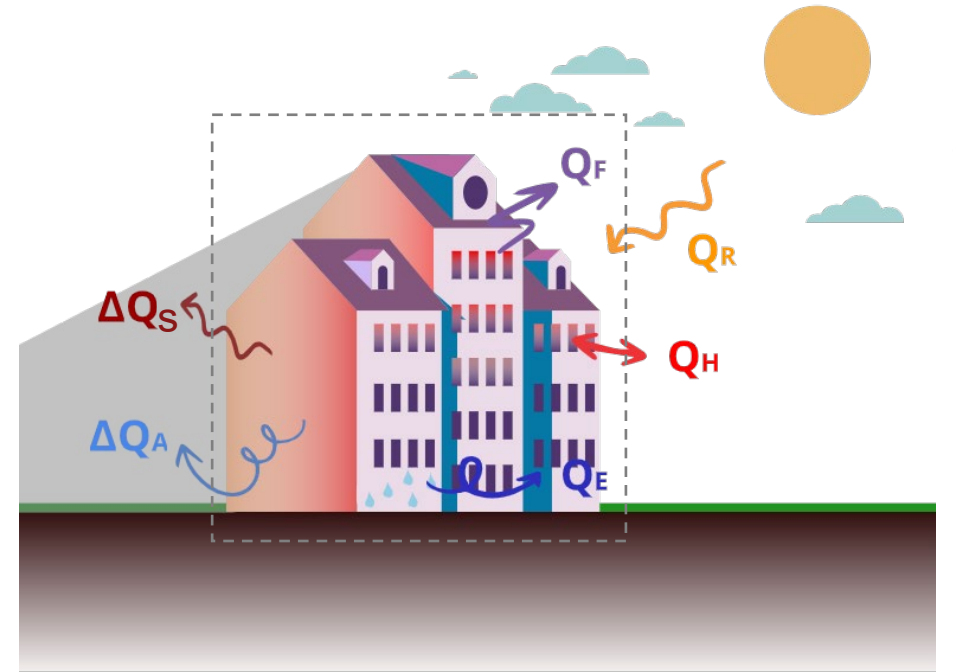
Picture from: [webservice](#)



Closed air gap illustration

# EPFL Urban Energy Balance: Control Volume approach

- A building *interacts* with the atmosphere, the Sun, the ground, other buildings and other urban elements (e.g., vegetation and water bodies).
- The **building interaction** with its environment is **always at balance**.
  - It is comprised of the radiation budget ( $Q^*$ ), anthropogenic heat ( $Q_F$ ), sensible heat ( $Q_H$ ), latent heat ( $Q_E$ ), stored heat ( $\Delta Q_S$ ), and advection ( $\Delta Q_A$ ).
- The **energy balance** is a **transient phenomena** (time-dependent).
  - **Each term** experiences **diurnal** and **seasonal** variation.
- Although the urban element is a combination of *surfaces*, the **energy balance** is *not only the sum of these surfaces* as these surfaces also *interact with each other*. Contrary to the SEB, **control volume energy balance** considers **the masses of the volume elements**.



$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \quad (1-3)$$

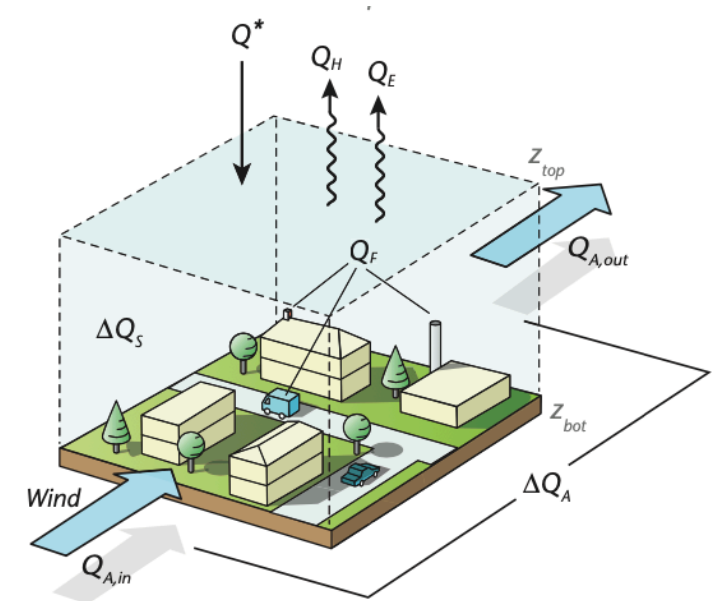
Radiation budget  
 Anthropogenic heat  
 Sensible heat  
 Latent heat  
 Stored heat  
 Advected heat

Reminder from L1

- Heat is stored in the urban structure *when air temperatures are high* (at day time, when  $T_{\text{ext}} > T_i$ )
- Heat is released from the urban structure *when air temperatures are low* (at night time when  $T_{\text{ext}} < T_i$ )

## Estimation of Urban Heat Storage $\Delta Q_S$ ( $W/m^2$ ):

- Energy Balance Residual Approach (RES):** requires solving Eqn. (1-3) for  $\Delta Q_S$  (see Eqn.6-1). Requires the measurements of all other parameters, assume that  $\Delta Q_A$  is small, has all the uncertainties and errors inherent in obtaining the other terms.
- Thermal Mass Scheme (TMS):** heat storage in a volume of the  $i$ -th urban component can be calculated from the basic concepts of heat conduction and heat storage (see Eqn. 6-2, 6-3).
- Numerical Simulation (TEB):** numerical solution of differential equations for heat conduction in the different facets of an urban canopy and link them to the SEB of the facet and temperature changes
- Parameterization:** {details in Oke, Urban Climates, p. 174}



Source: Oke, Urban Climates, p. 157

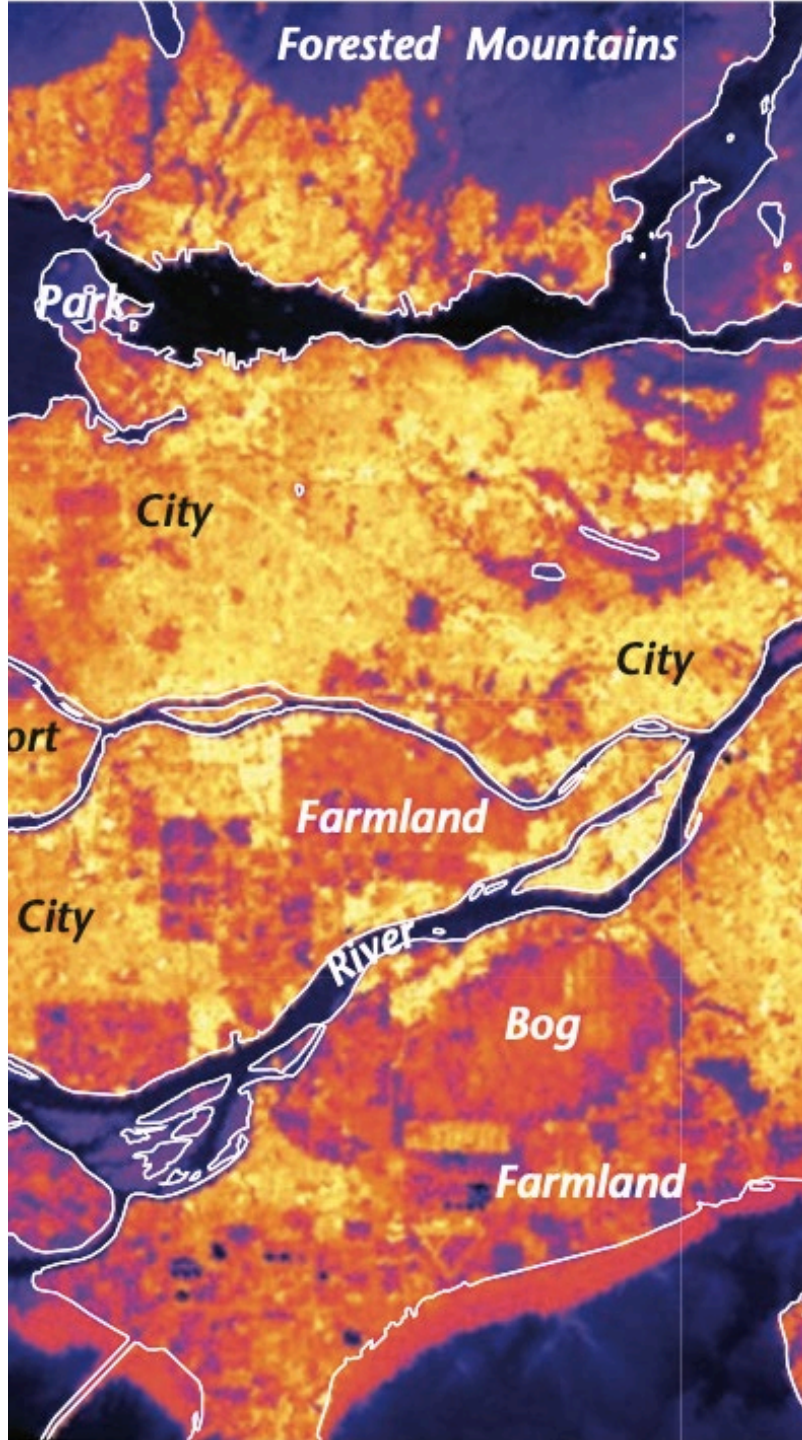
$$\Delta Q_S = Q^* + Q_F - Q_H - Q_E \quad (6-1)$$

Change in temperature  
over a given time period

$$\Delta Q_{S,i} = \frac{1}{A_i} \cdot \int_0^V C_{p,i} \frac{dT}{dt} dV \quad (6-2)$$

Heat storage change

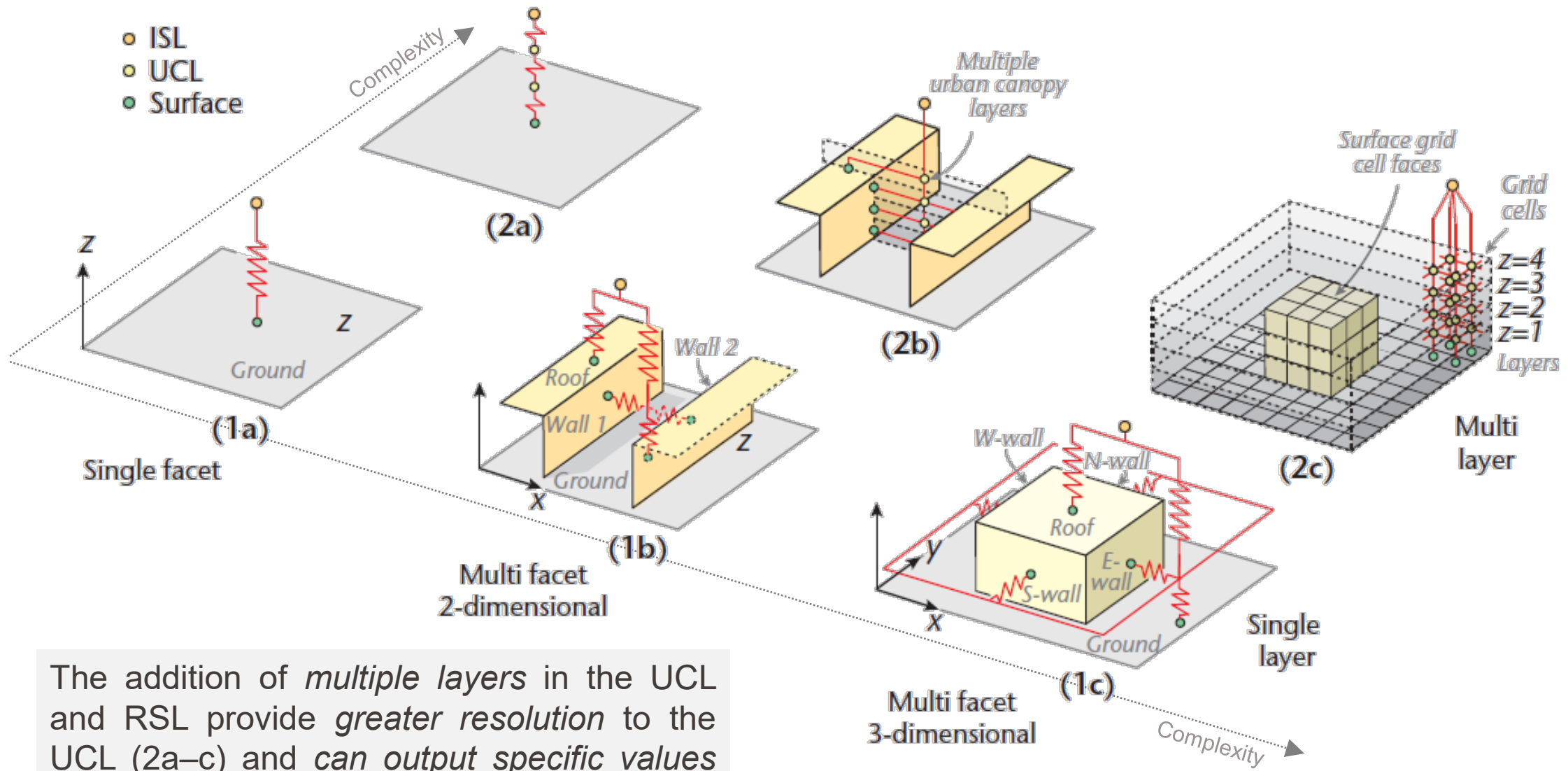
$$\Delta Q_S = \sum_i^N \Delta Q_{S,i} \quad (6-3)$$



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# Urban Canopy: Heat Exchange Analysis



The addition of *multiple layers* in the UCL and RSL provide *greater resolution* to the UCL (2a–c) and *can output specific values* for screen-level, mid-canyon, roof-level, etc.

# Urban Canyons: Sensible Heat Exchange ( $Q_H$ )

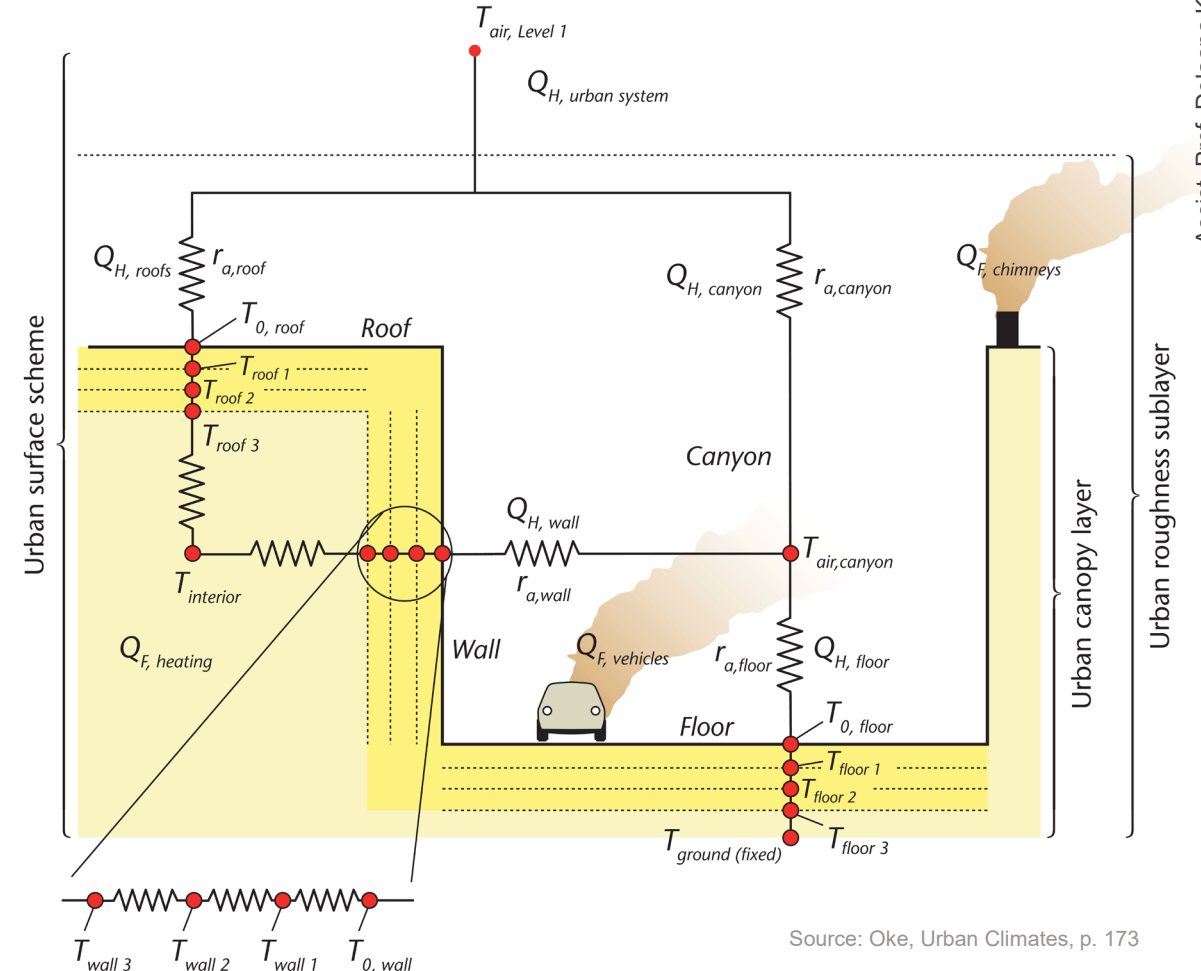
- Analysis of the **sensible heat  $Q_H$**  (conduction + convection) in the **urban canopy** can be focused on **canyon-plus-roof system** considering a **network of thermal resistances** involving **walls, roof surfaces, and a street in-between**.
- Thermal resistance** of the  $i - th$  element (e.g., a wall, a roof) having **conductive heat transfer** through  $n$  number of layers in a series:

$$R_i = R_{i,1} + R_{i,2} + \dots + R_{i,n} \quad (3-6b)$$

- The **total thermal resistance** of the system when **multiple pathways exist** (e.g., simultaneous heat conduction through the walls, windows, and a roof):

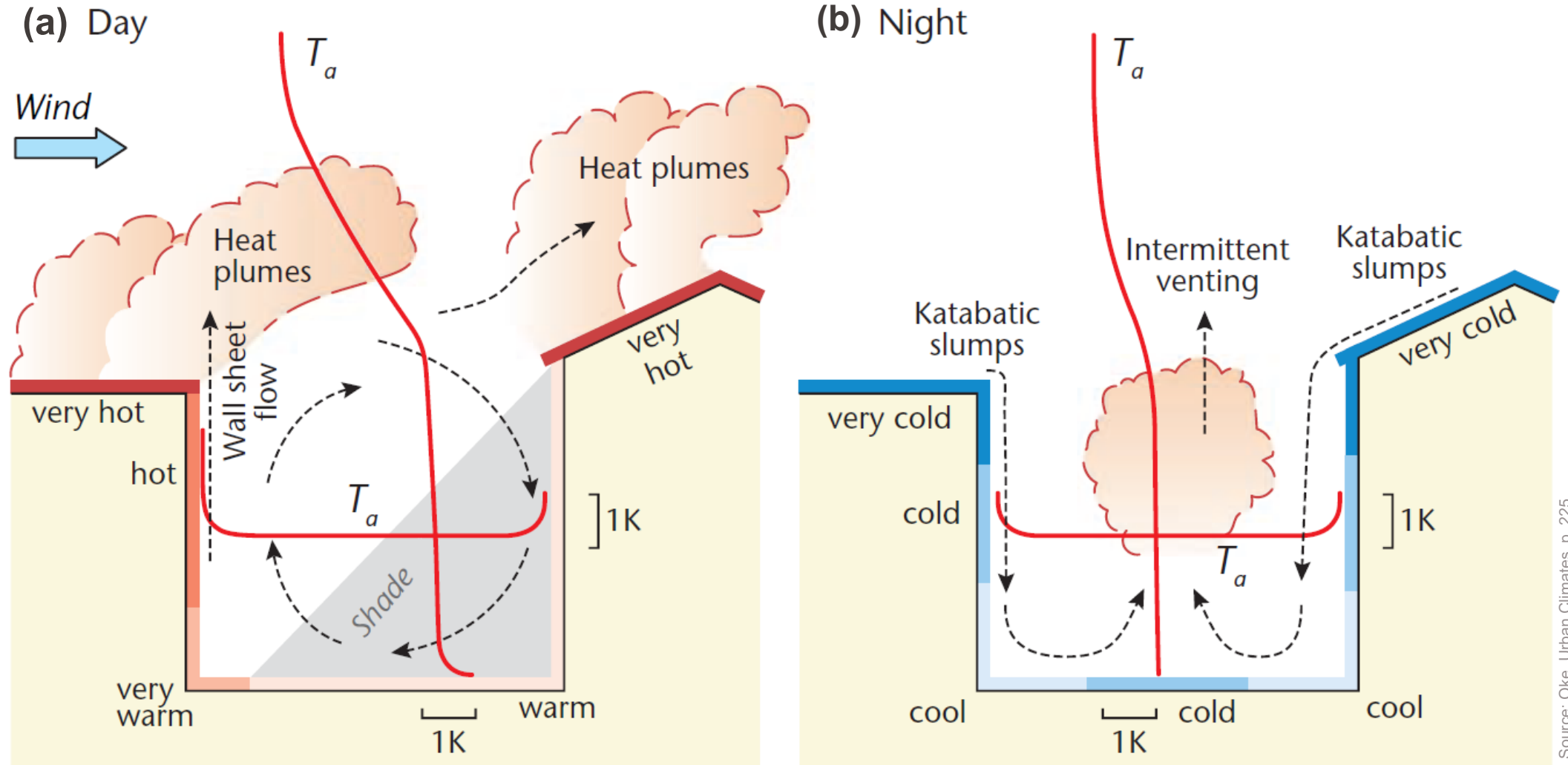
$$\frac{1}{R_{tot}^*} = \frac{1}{R_1^*} + \frac{1}{R_2^*} + \dots + \frac{1}{R_N^*} \quad (3-7b)$$

\* The resistances need to be *weighted* by the *areal fraction* of *different surfaces*.



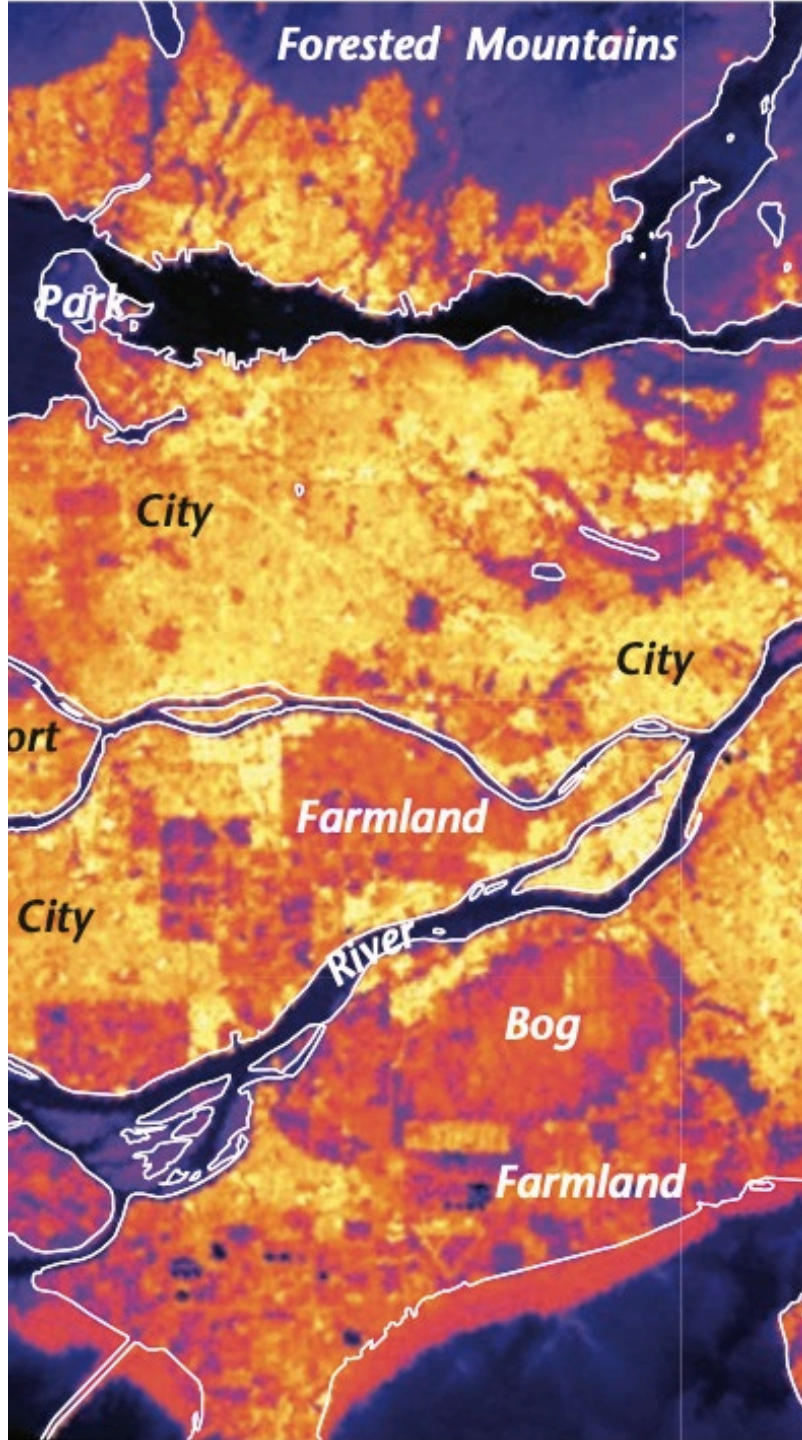
Source: Oke, Urban Climates, p. 173

# Urban Canyons: Sensible Heat Exchange ( $Q_H$ )



Source: Oke, Urban Climates, p. 225

Schematic representation of *typical diurnal sequence* of **vertical profiles of air temperature** in the UCL and RSL of an urban area in (a) **daytime**, (b) **at night** (on a day with light winds and little or no cloud).



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# EPFL Urban Canyons: Shortwave Radiation Exchange ( $K^*$ )

- Urban surface exposed to **shortwave** (direct and diffuse) radiation flux [see L3, slides 29-30 for a surface]:

$$K_{\downarrow,i} = S_i + D_{sky,i} + D_{env,i} \quad (3-32b)$$

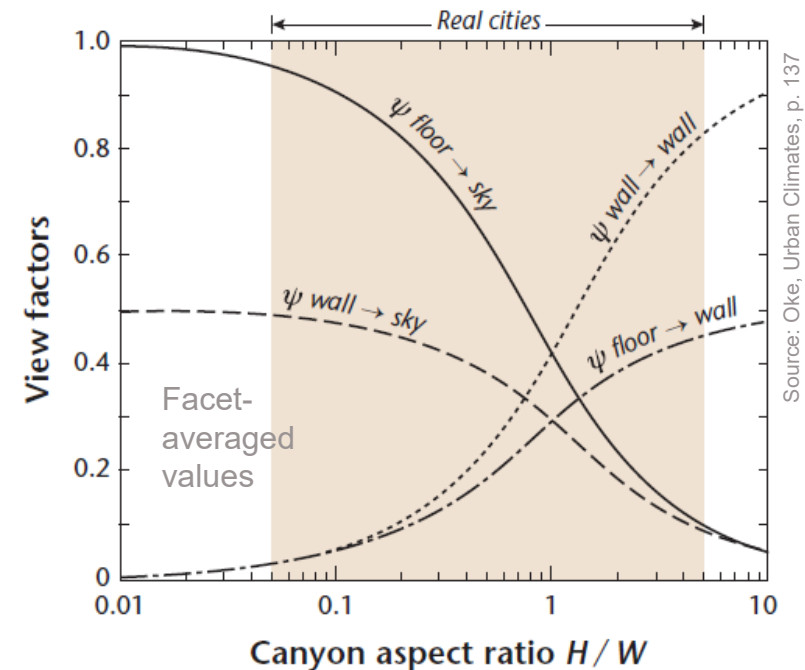
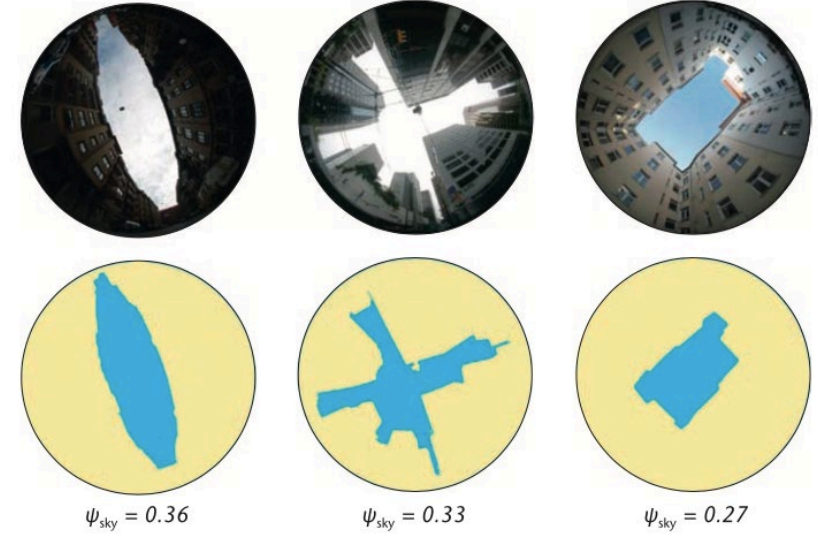
- Diffuse irradiance from the sky ( $D_{sky,i}$ )** entering the urban environment and reaching the urban surface ( $i$ -th) mainly depends on the **sky view factor  $\psi_{i \rightarrow sky}$** :

$$D_{sky,i} = D_{sky,0} \cdot \psi_{i \rightarrow sky} \quad (6-4)$$

$D_{sky,0}$  - diffuse radiation on a horizontal surface with an unobstructed sky view

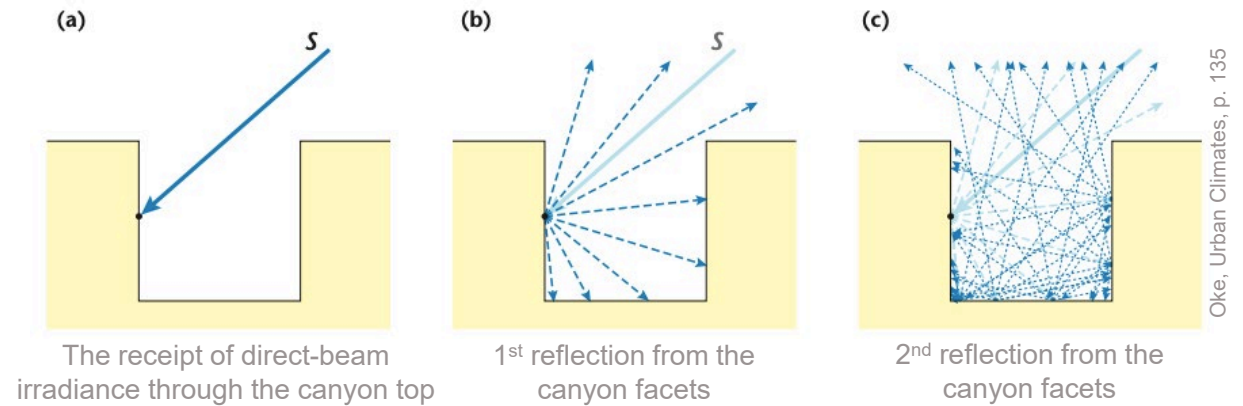
- Urban contribution to diffuse shortwave irradiance ( $D_{env,i}$ )** is the integral of all reflection events that impinge on the surface. The complex urban geometry leads to heterogeneous distribution of diffuse radiation, hence urban surfaces are commonly divided into smaller units ( $j$ ) to determine their individual contribution:

$$D_{env,i} = \sum_{j=1}^{N-1} K_{\uparrow,j} \cdot \psi_{i \rightarrow j} \quad (6-5)$$



# EPFL Urban Canyons: Shortwave Radiation Exchange ( $K^*$ )

- Urban diffuse irradiance in urban canyons is shortwave radiation reflected from its surfaces:
  - Once direct-beam enters the canyon, it is reflected *ad infinitum* with progressively less energy being exchanged, because each surface absorbs a portion of the radiation they receive.



Oke, Urban Climates, p. 135

- The narrower a street canyon is...
  - View factor  $\psi_{i \rightarrow env}$  increases while the factor  $\psi_{i \rightarrow sky}$  decreases
  - The more shortwave radiation will be reflected and absorbed
  - The lower albedo of a canyon than that of its constituent facets
  - The greater global radiation budget ( $Q^*$ ) increase
- Direct solar radiation should be prevented from reaching urban surfaces by shading urban elements.
  - Shading should not reflect shortwave radiation toward the canyon



Urban form	H/W	$\lambda_c$	Albedo $\alpha$	Change in absorption
	0	1	0.40	
	0.5	1.5	0.32	+17%
	1	2	0.27	+21%
	2	3	0.23	+27%

Source: Oke, Urban Climates, p. 140

# EPFL Urban Canyons: Longwave Radiation Exchange ( $L^*$ )

- Incoming longwave radiation reaching the  $i$  – th urban surface:

where  $L_{\downarrow,sky,0}$  - incoming longwave radiation on a horizontal surface with an unobstructed sky view

$$L_{\downarrow,i} = L_{\downarrow,sky,0} \cdot \psi_{i \rightarrow sky} + \sum_{j=1}^N (L_{\uparrow,j} \cdot \psi_{i \rightarrow j}) \quad (6-6)$$

Input from the portion of the sky hemisphere “seen”

Input from the surrounding environment

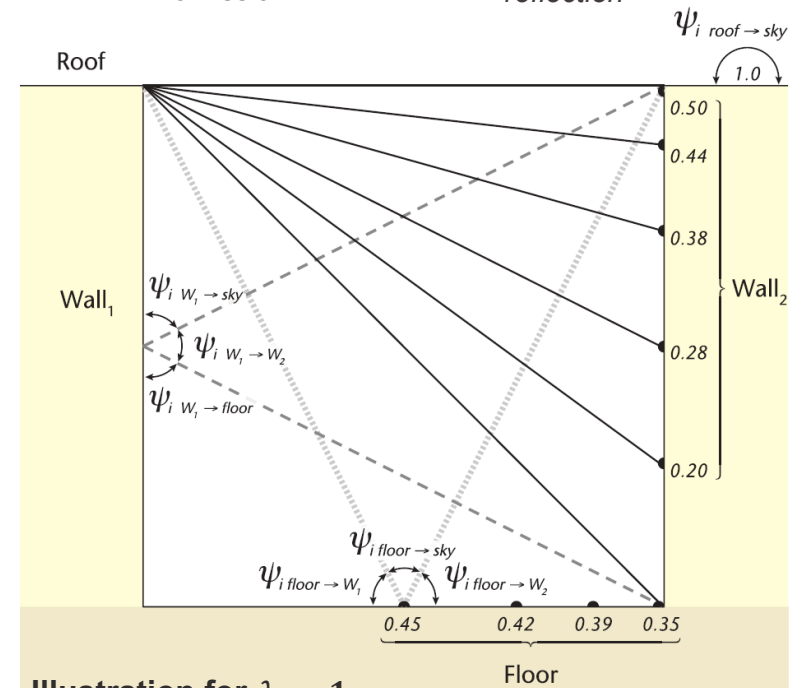
- Outgoing longwave radiation from the  $j$  – th urban surface (opaque surface):

$$L_{\uparrow,j} = \underbrace{\varepsilon_j \cdot \sigma \cdot T_j^4}_{\text{emission}} + \underbrace{(1 - \varepsilon_j) \cdot L_{\downarrow,j}}_{\text{reflection}} \quad (3-39b)$$

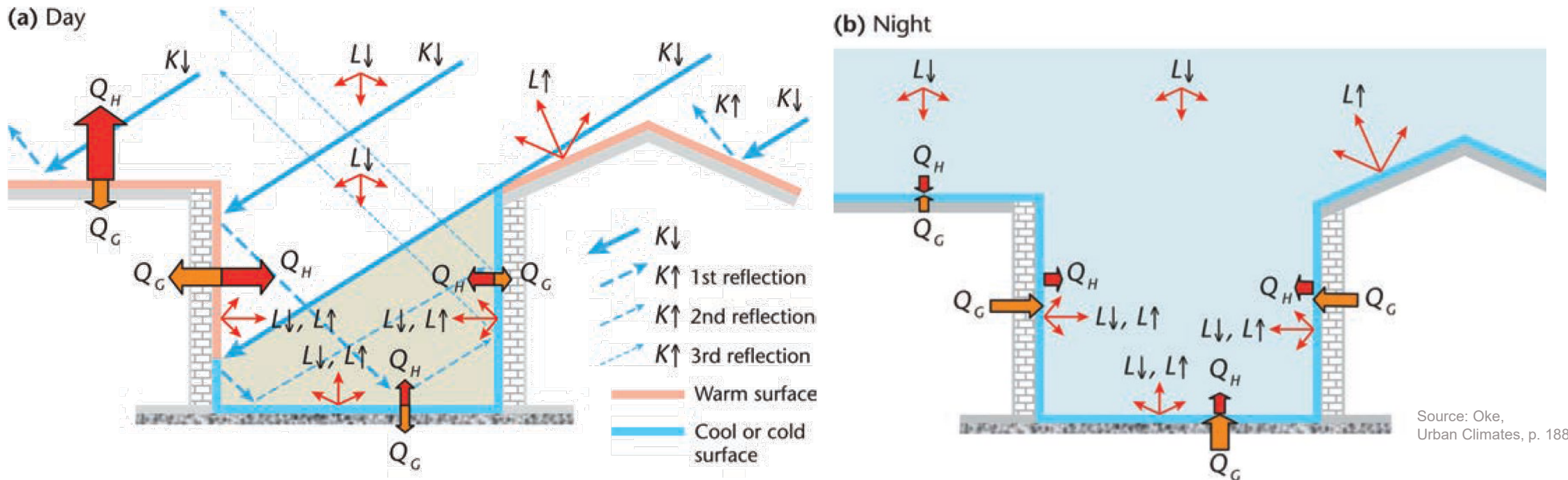
- In urban canyons, the behavior of all surfaces is mutually dependent (e.g.,  $L_{\downarrow,j}$  depends on  $L_{\downarrow,i}$ )

- Effect of the  $\psi_{i \rightarrow sky}$  view factor:

- Canyons with high  $\lambda_s$  (small  $\psi_{i \rightarrow sky}$ ): the portion of  $L_{\uparrow,i}$  escaping the canyon is small (mainly intercepted and absorbed by other surfaces)
- Portion of the  $L_{\downarrow}$  from the “cold” sky is small, most input from relatively warm surfaces
- Cooling is small at the bottom of canyons with high  $\lambda_s$  (deep and narrow).



# EPFL Urban Canyons: Radiative Heat Exchange ( $Q^*$ )



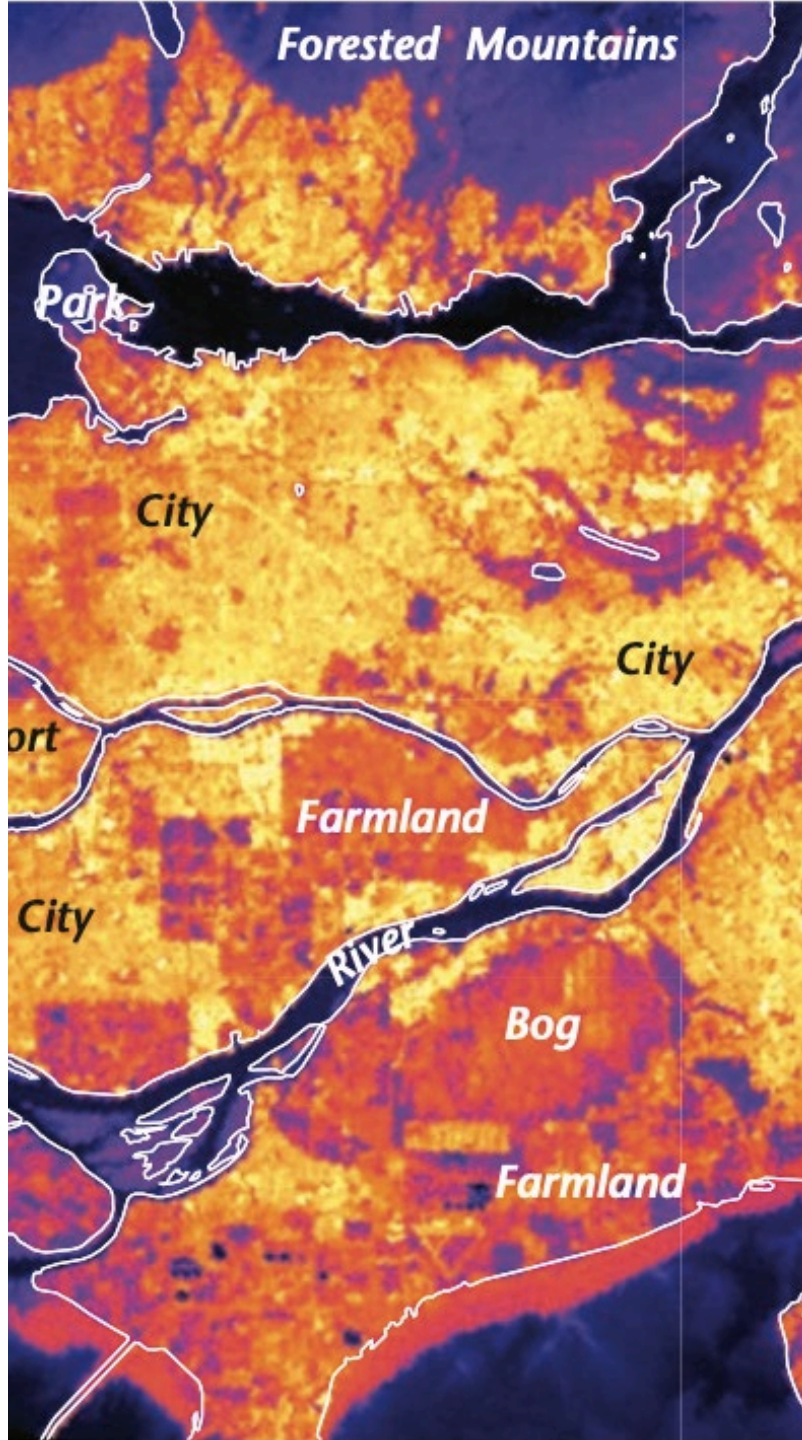
Source: Oke, Urban Climates, p. 188

## Daytime exchange within the canyon:

- Restricted solar irradiance, depends on shadow patterns (function of Sun-Earth geometry, canyon orientation, and  $\lambda_s = H/W$  ratio). The larger  $\lambda_s$ , the smaller is average solar access.
- Multiple reflection between facets increases overall absorption of both short- and longwave radiation.
- The walls and floor (=ground), having high thermal admittance  $\mu$ , store heat.

## Nighttime exchange within the canyon:

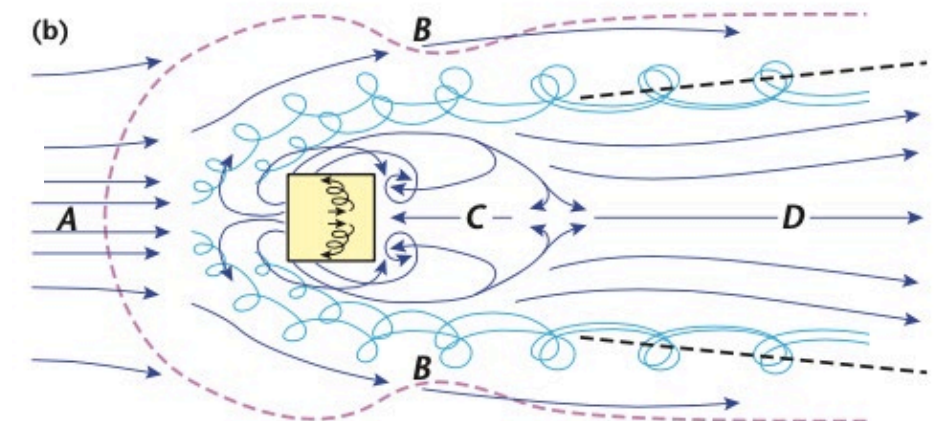
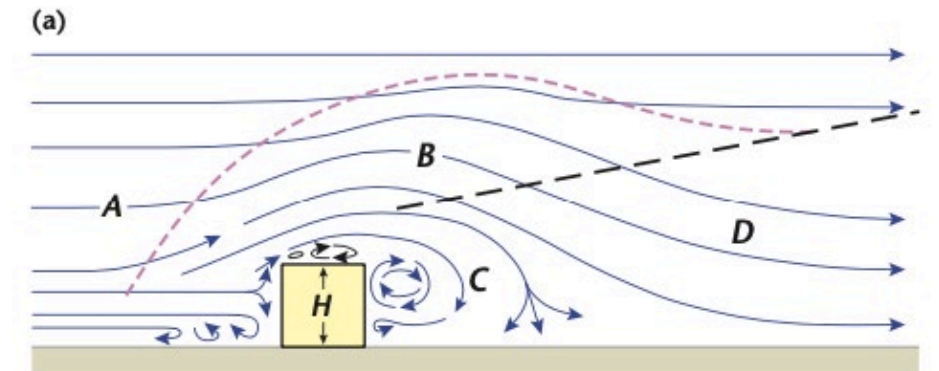
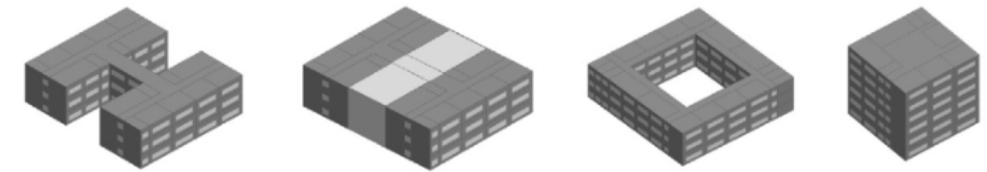
- Longwave radiation budget  $L^*$  is negative ( $L\downarrow < L\uparrow$ )
- Cooling is weaker within the canyon than at the roof-level, because of the reduced sky view factor and dissipation of the heat stored. The strength of cooling is controlled by:
  - Antecedent temperatures of canyon facets
  - $\lambda_s$  (sets the sky view and the view factor of surfaces)
  - Emissivity values of surfaces
  - Effective radiating temperature of the sky (controlled by cloud cover)



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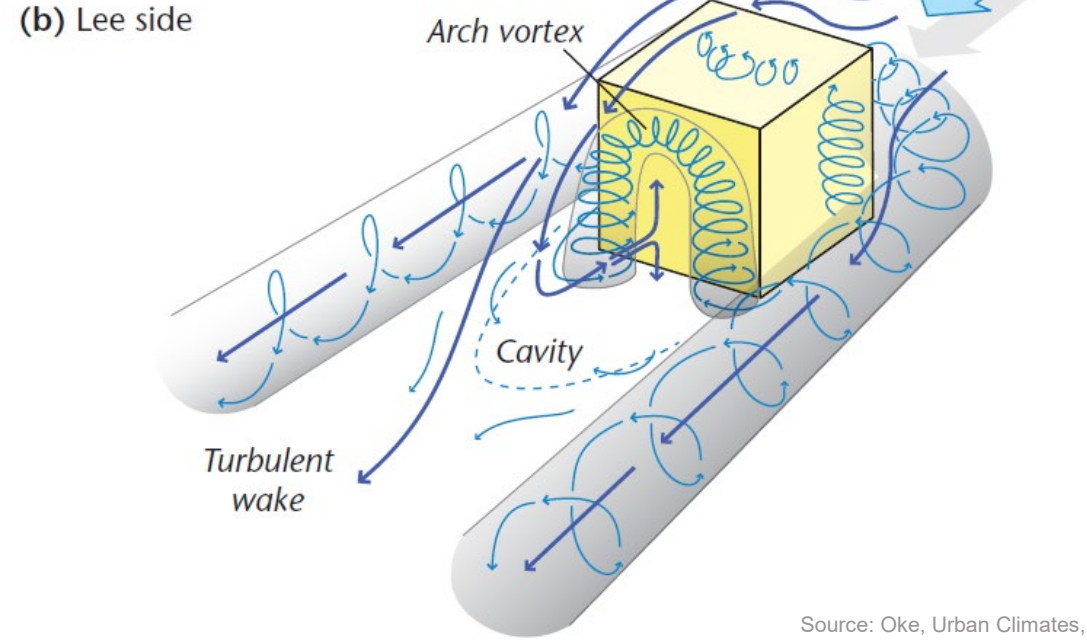
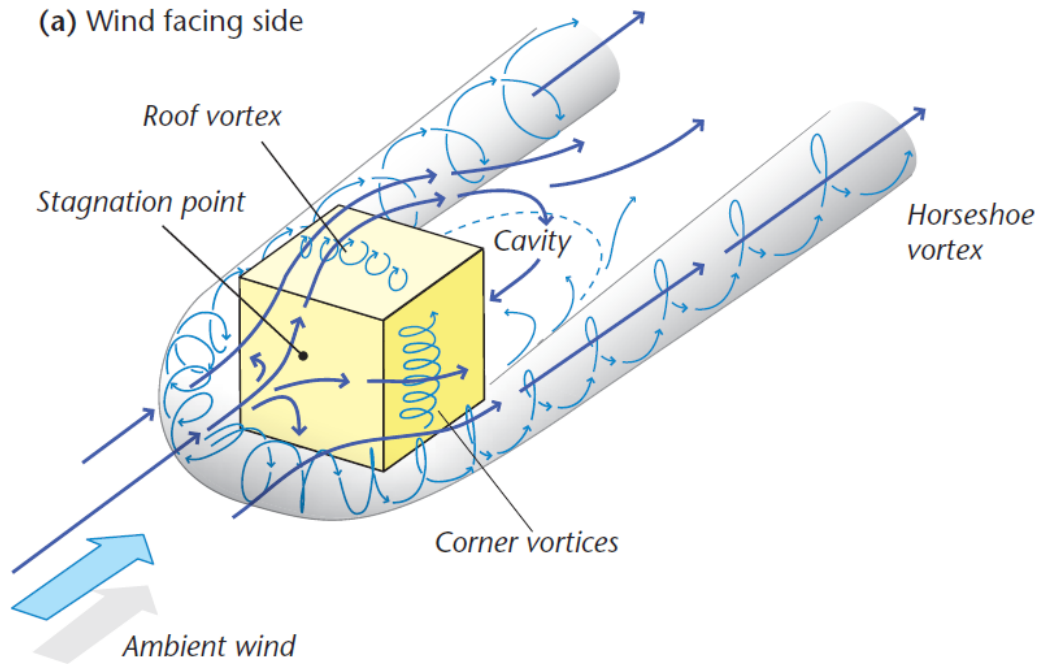
- **Importance of understanding the air flow around buildings:**
  - To control **the heat dissipation** due to the wind flow around building (elevated convection is avoided in cold seasons but preferred in warm seasons).
  - To **control the wind speed** entering *the building ventilation*.
  - To control **particle dispersion** and **pollution stagnation**. Wind and **mixing** is encouraged in the area of high pollution density.
  
- Buildings induce **roughness** and complex **3D wind patterns** (on a flat terrain, the wind flow is *mostly horizontal*), wind profile is deformed.
  
- **The air flow behavior around a single building:**
  - **Deflected** *around* and *above* the building
  - **Detaches** on *sharp edges* or when *wind speed is high* (**flow separation**)
  - **Recirculates** in *low pressure* regions.



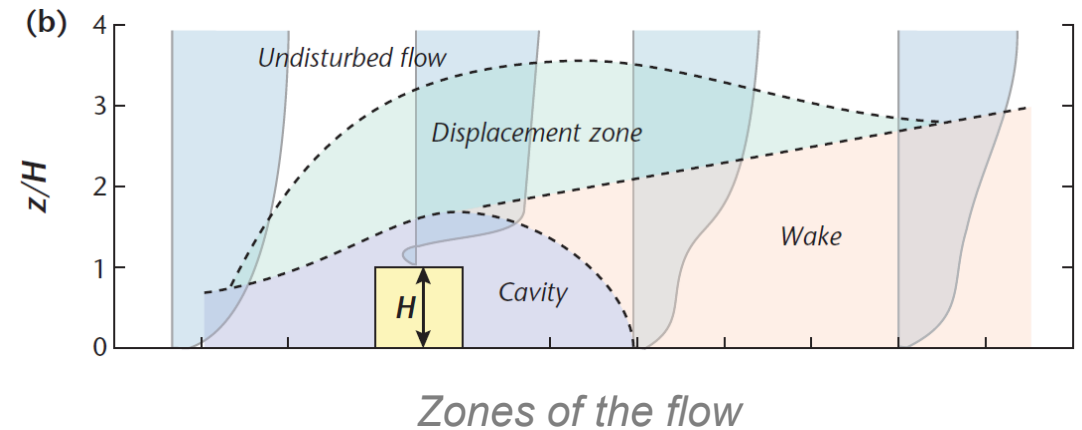
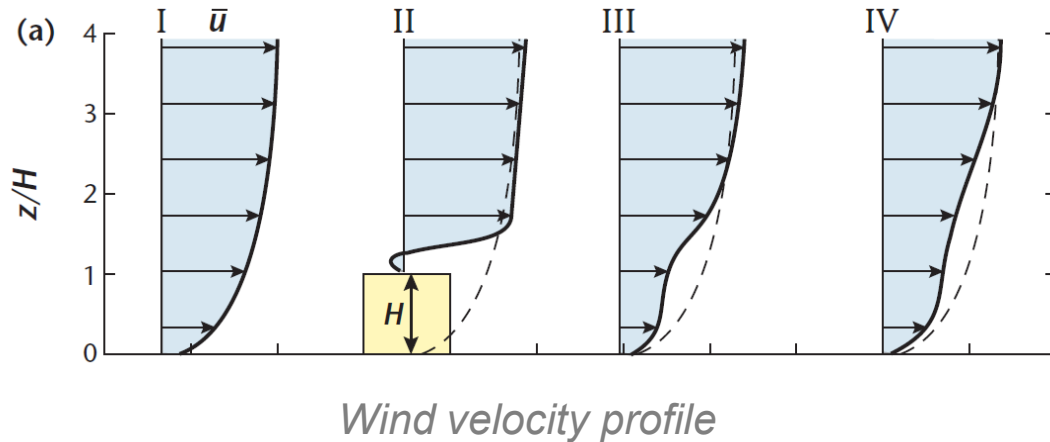
- Video illustration: <https://www.youtube.com/watch?v=UEgk2Bgz16s>



# Aerodynamic Interaction: Isolated Buildings



Source: Oke, Urban Climates, p. 84



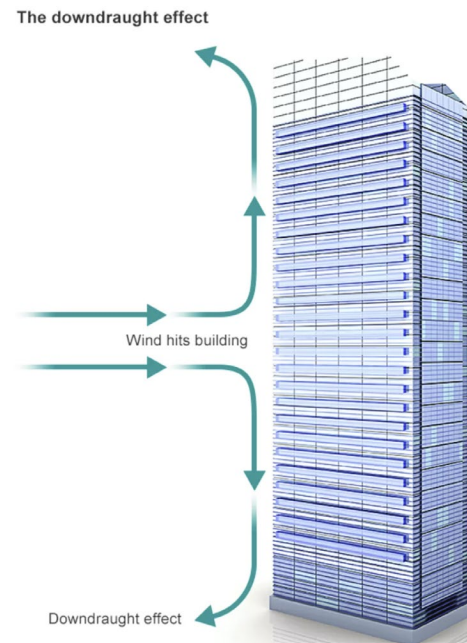
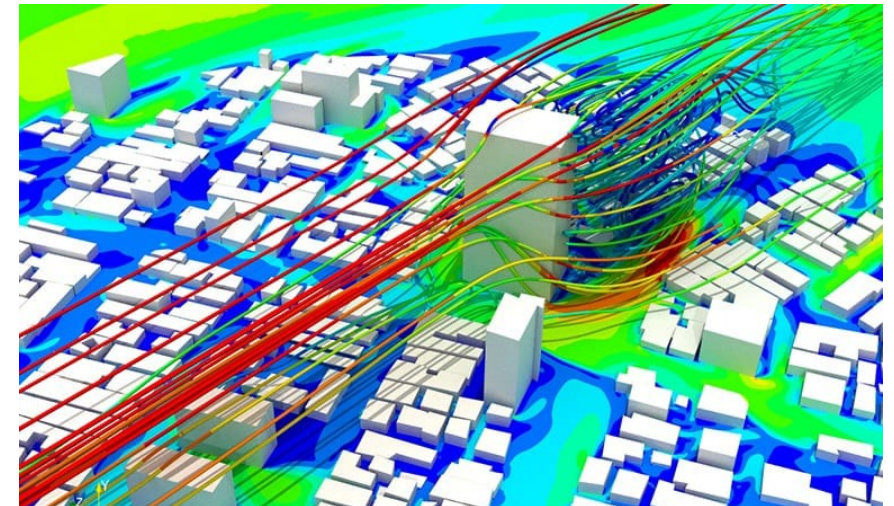
Oke, Urban Climates, p. 85

- The effect of **tall buildings** on the wind are *stronger* compared to the moderate-sized buildings:
  - The magnitude of **the perturbation** to the **pressure** and **velocity** fields can be greater and the momentum injected downward is potentially larger, *strong blasts* occur at building sides, the stagnation point is at higher level.
  - Tall buildings *deflect the strong high-altitude wind to pedestrian level on punctual zones* (a pedestrian can suddenly encounter a blast of strong wind sufficient to knock him over).



Source: Oke, Urban Climates, p. 86

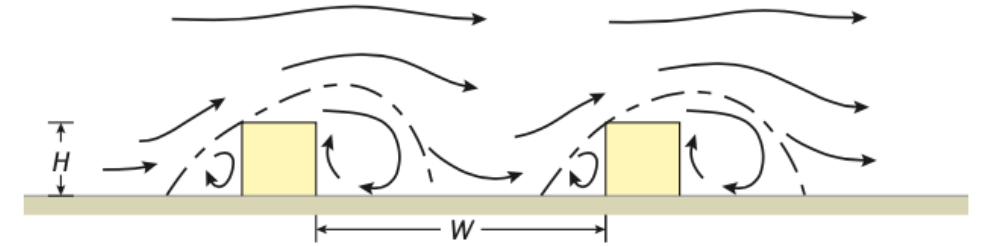
- Tall buildings are required to first be *simulated* and *experimented* with wind tunnels.
- **A few advantages of tall buildings:**
  - They *cool down* the neighboring area due to high convection
  - They have a potential to *clean* the air by substantial mixing

<https://www.bbc.com/news/><https://www.simscale.com/blog/pedestrian-wind-comfort-validation/>

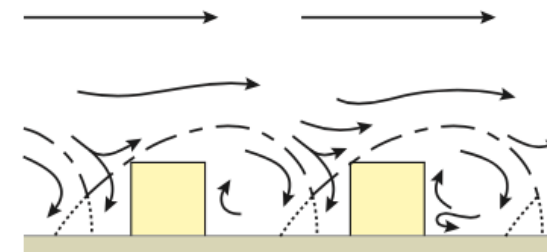
- The *distance between buildings*, their *height* and the *wind velocity* determines the *interaction between the respective wakes* of the buildings:

- Widely spaced buildings ( $H/W < 0.35$ ):** individual wakes *don't interact* with each other.
- Closely spaced buildings ( $0.35 < H/W < 0.65$ ):** vortex in the cavity behind the upwind building is reinforced by the flow down the windward face of the next building.
- Densely spaced buildings ( $H/W > 0.65$ ):** the above-roof flow "skips" across the tops of the buildings with *less tendency* to enter into the street canyons (the flow above the roofs is decoupled from that in the canyons).

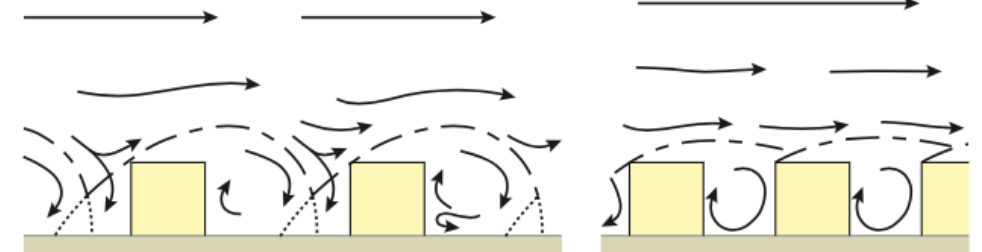
(a) Isolated roughness flow



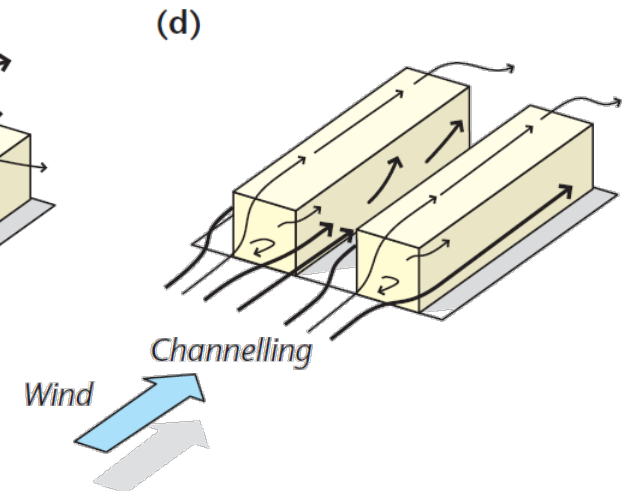
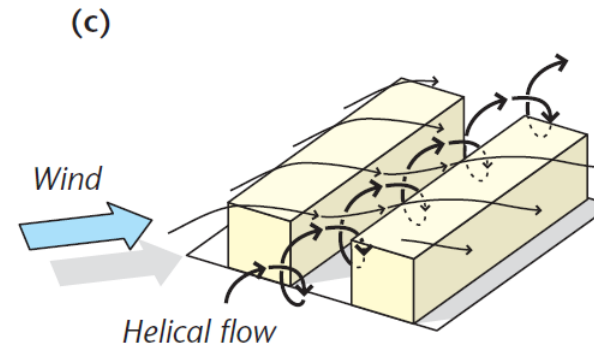
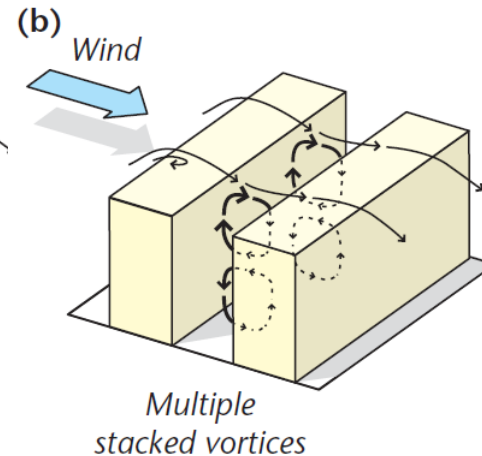
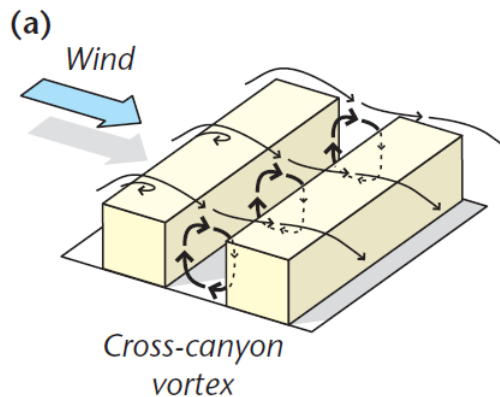
(b) Wake interference flow



(c) Skimming flow

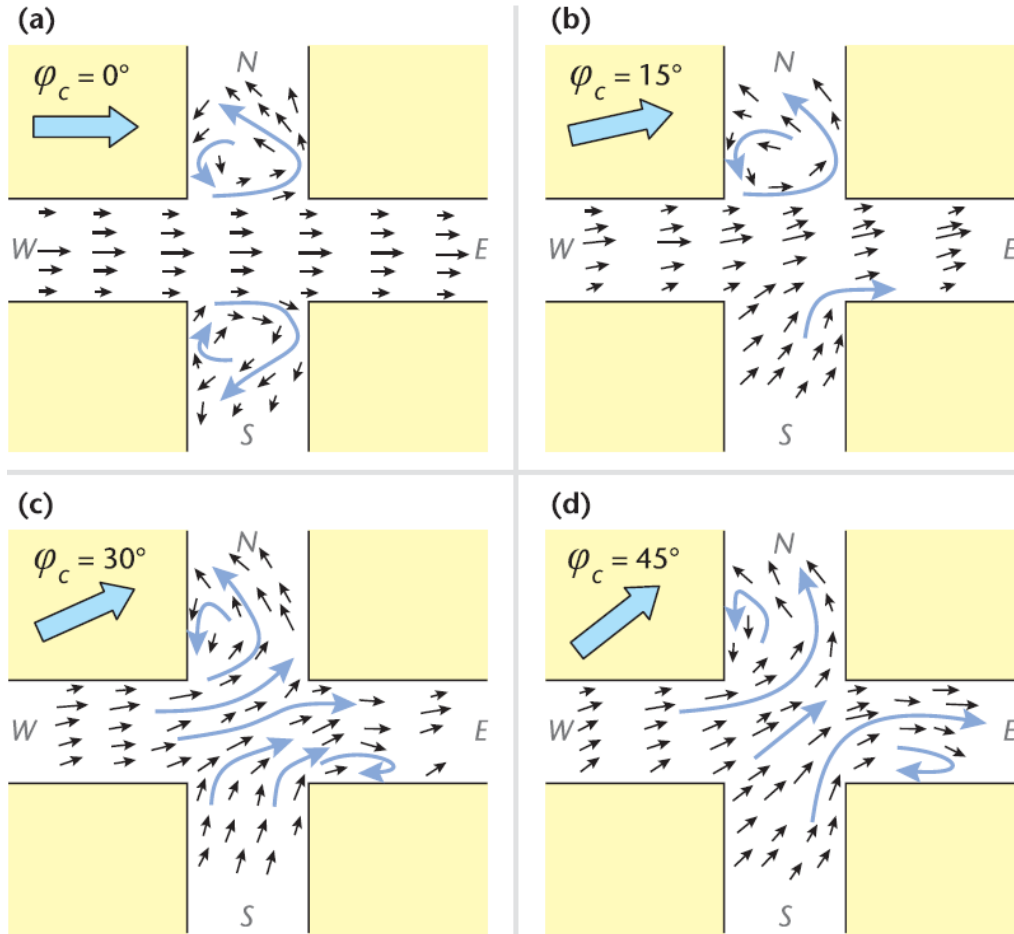


Source: Oke, Urban Climates, p. 88



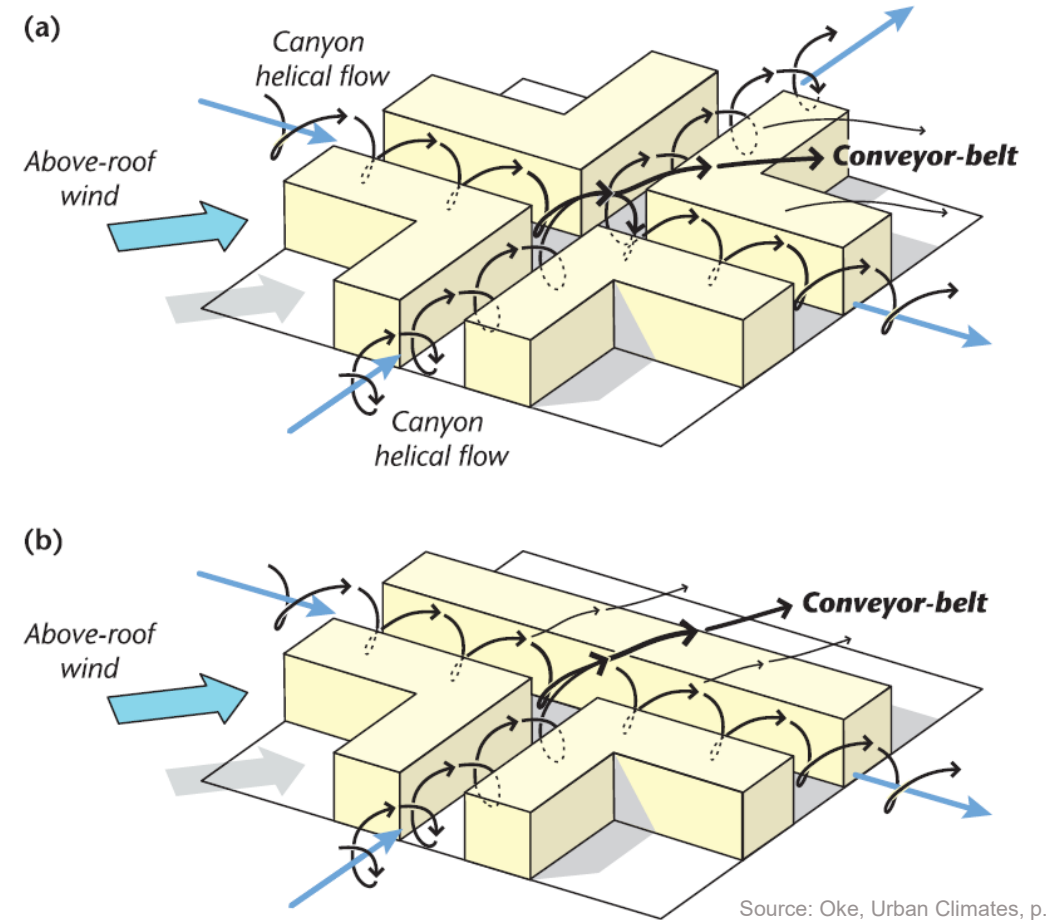
Source: Oke, Urban Climates, p. 89

# Aerodynamic Interaction: Urban Canyons



Source: Oke, Urban Climates, p. 91

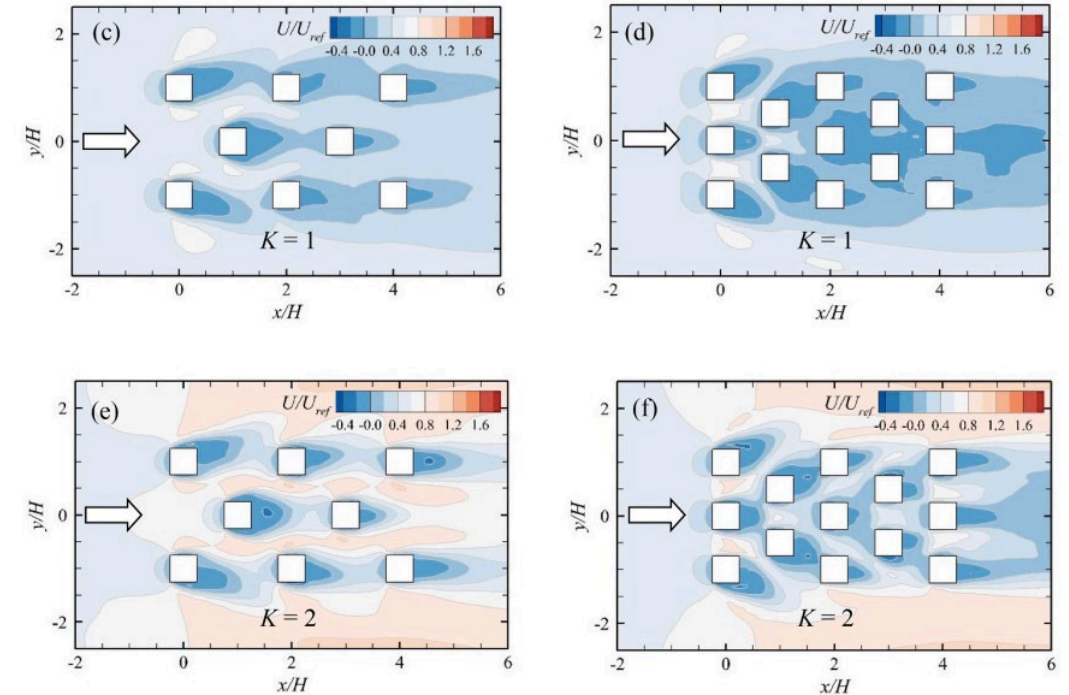
Typical flow patterns in a 4-way street intersection (numerical simulations of mean horizontal velocity at half canyon height): (a)  $0^\circ$ , i.e. parallel to the east-west street, (b)  $15^\circ$ , (c)  $30^\circ$ , (d)  $45^\circ$



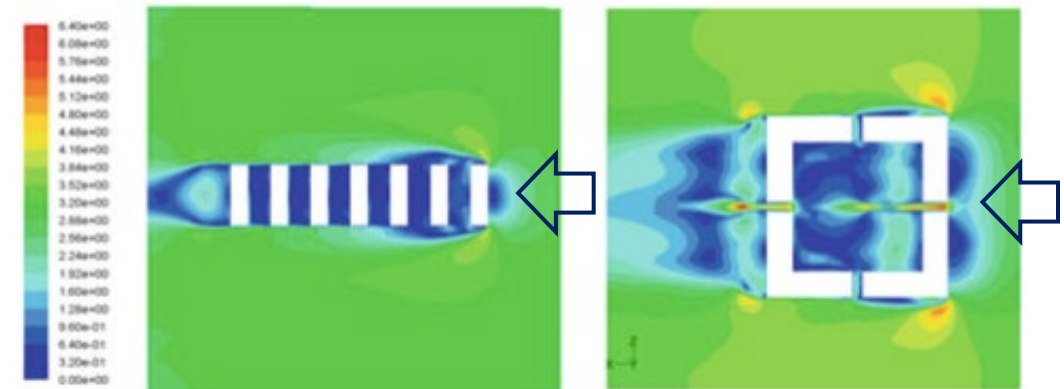
Source: Oke, Urban Climates, p. 92

Schematic depiction of 3D flow at (a) an intersection on an orthogonal street grid with above-roof flow diagonal to the grid, (b) similar, but at a T-junction. Light blue arrows show the mean flow direction whilst the black arrows depict the actual helical motion.

- The geometric design of urban districts has an influence on the flow pattern **downwind**.
- The *relative placement* of buildings change the wind flow patterns. Factors are: **their spacing, alignment, rotation, and height**.
- Narrow street canyons *trap* the wind coming *transversally* or *prevent it from entering* the canyon. They create a wind tunnel for wind coming *longitudinally* (**channeling**).
- The wind flow interference with buildings *modify the wind profile*.
  - Wind profile is deformed by the front buildings (**windward buildings**), and the **downwind** buildings are *streamlined* by deformed wind profile.
- As *bursts of wind* are avoided but *mixing* is favored, a *scattered formation* of buildings is preferred.



Source: LiU ET AL. (2021) <https://doi.org/10.1016/j.buildenv.2021.107625>



Source: Medved, Building Physics, p. 463

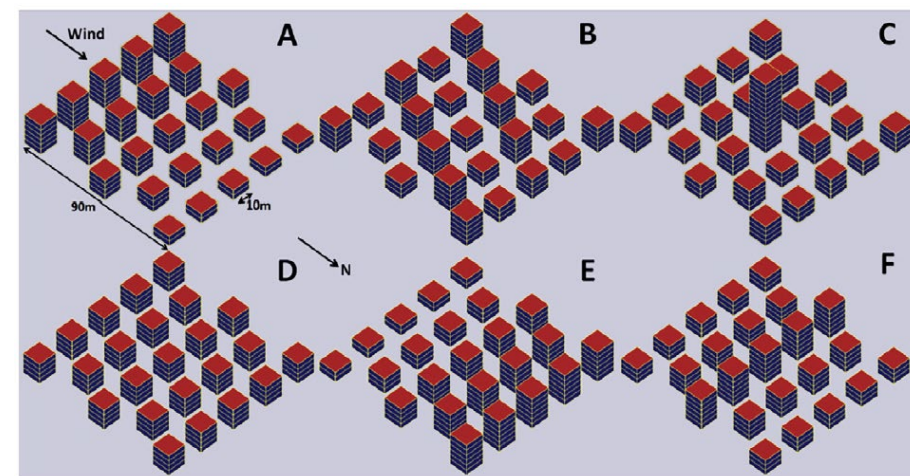
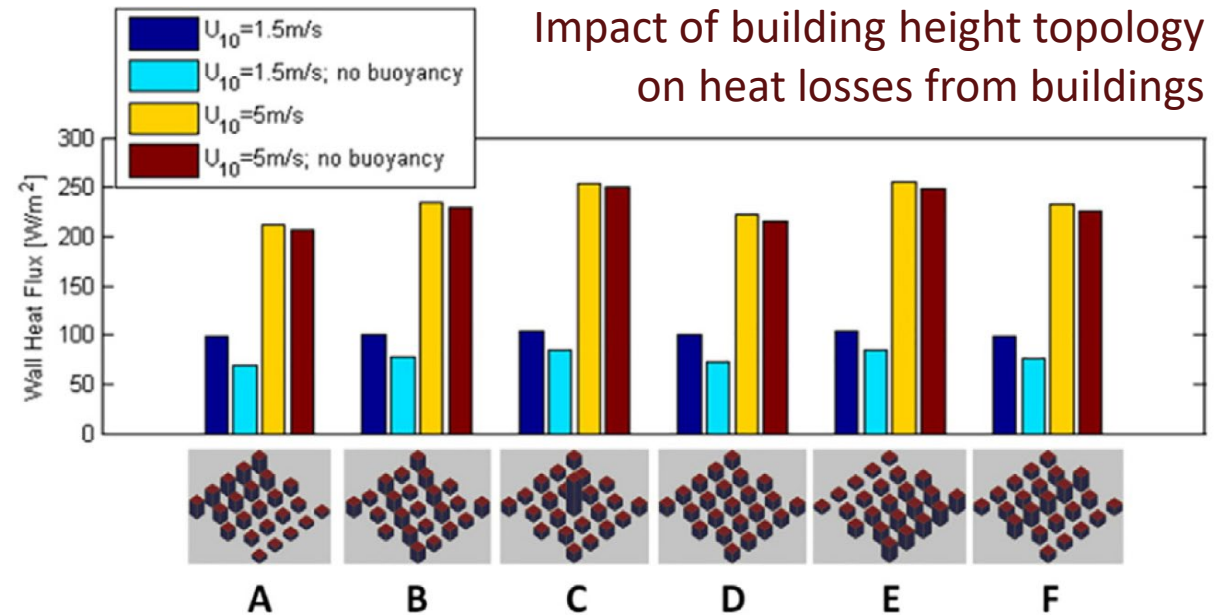
# EPFL Aerodynamic Interaction: Convective Heat Exchange

- Convective heat dissipation from surfaces:

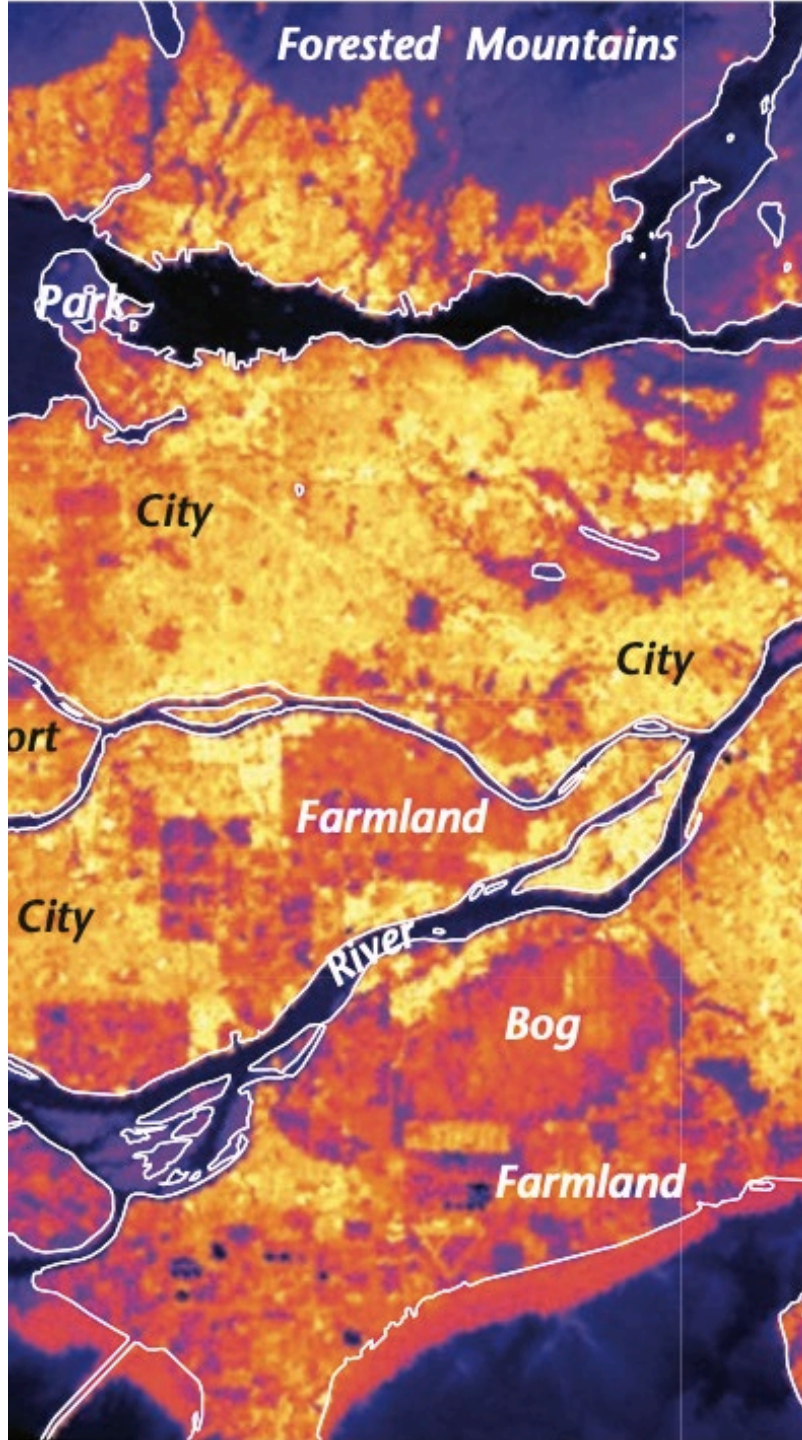
- Summer:** convection can be *advantageous* to *naturally cool* the buildings (air temperature should be lower than indoor temperature)
  - Winter:** to reduce heat losses from building toward outdoors, *increased convection at the outer interface is avoided*

- Heat removal by convection:

- Increases with wind speed due to *forced convection* at high wind speed (e.g.,  $V > 0.5$  m/s)
  - Buoyancy* is stronger for low wind speeds, negligible at high wind speeds.



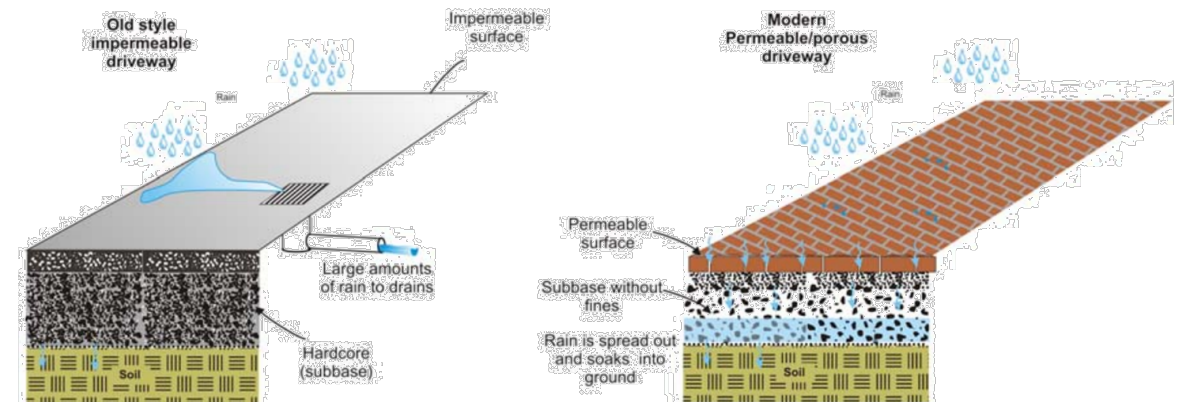
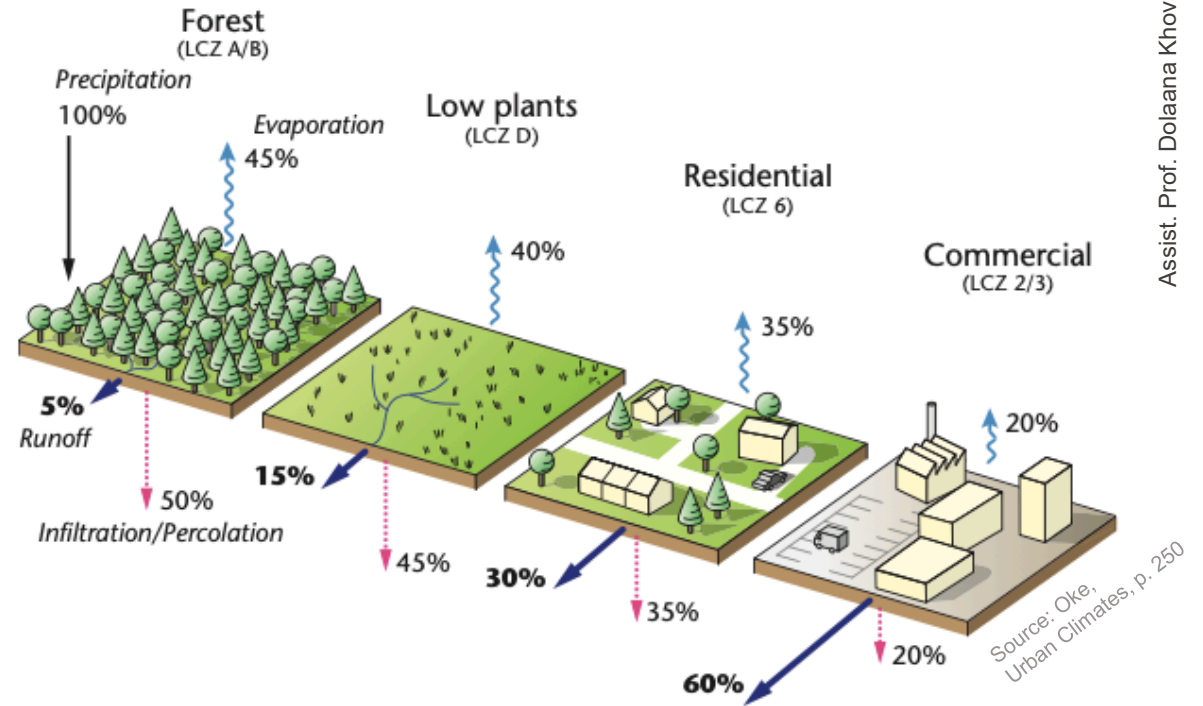
Source: Allegrini & Carmeliet (2017) <http://dx.doi.org/10.1016/j.uclim.2017.07.005>



# CONTENT:

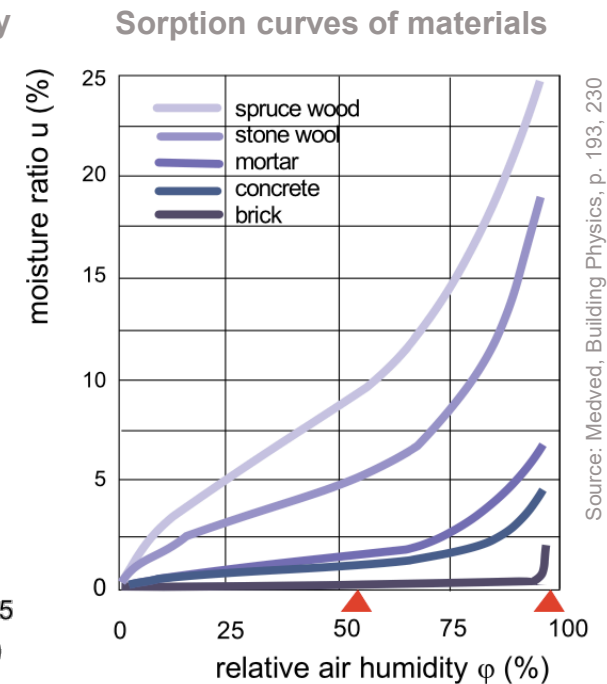
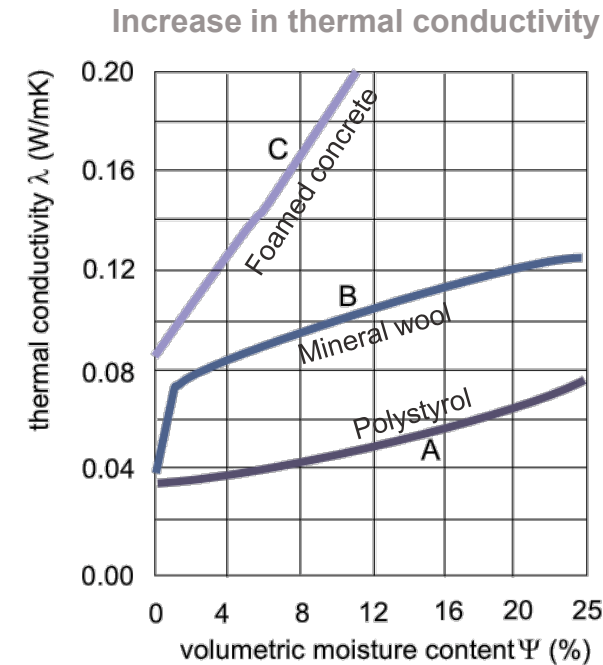
- I. Introduction
- II. Urban energy balance and heat storage
- III. Urban canyon sensible heat exchange
- IV. Urban canyon radiation budget
  - Shortwave vs. longwave radiation
- V. Aerodynamic interaction
- VI. Hydrodynamic interaction

- **Evaporation** is *smaller* in cities than in their countryside during the day, hence **humidity being smaller as well**.
  - If less evaporation takes place, more sensible heat is generated.
- Differences of water organization in urban areas compared to rural areas:
  - **Runoff** is greater due to more *impermeable surfaces* (asphalt, concrete, stone, pavers)
  - **Storage of water** is less due to less water from precipitations available.
  - **Evaporation** of water is less due to *less water* available.
- Only water present in the urban atmosphere and at surfaces can be evaporated. Surface water is:
  - *Freely available* at ponds and lakes
  - *Held by a surface* in the pores of *the materials*



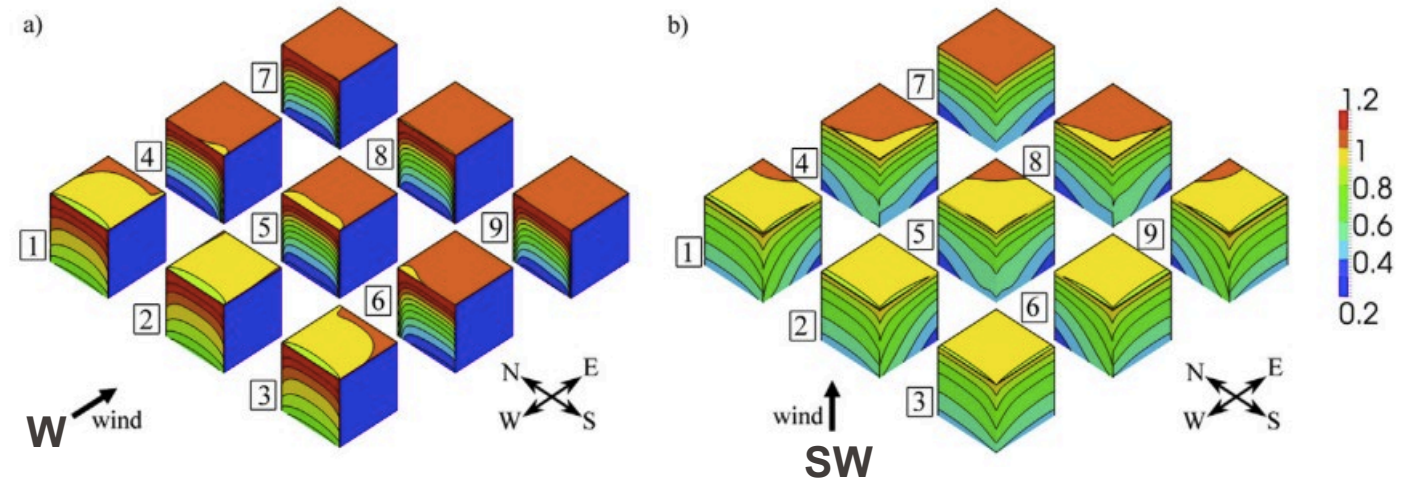
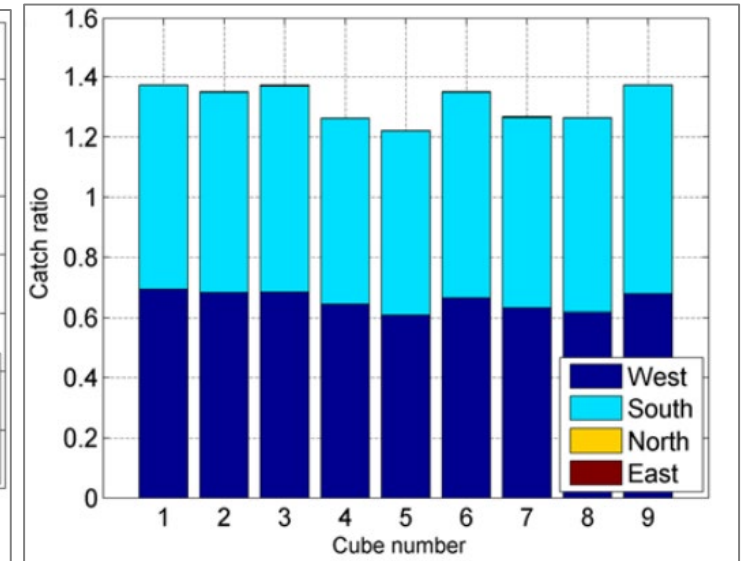
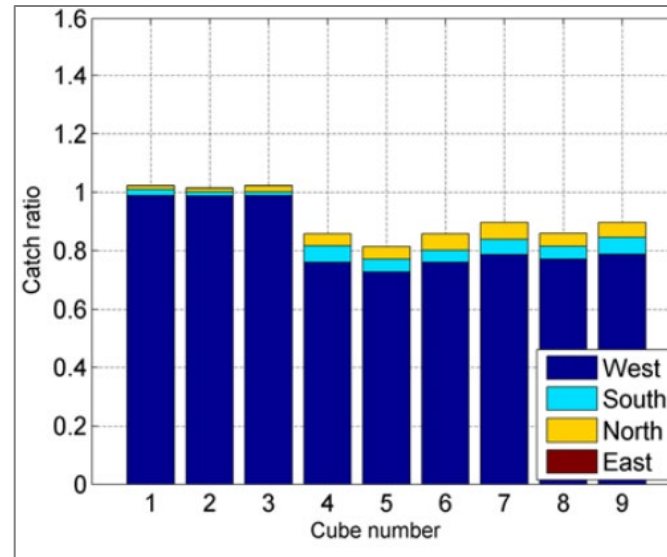
Source: <http://data.parliament.uk/DepositedPapers/Files/DEP2010-0563/DEP2010-0563.pdf>

- **Building materials retain water:**
  - They *absorb and release* water
  - They *condensate* water at their surface
- Water infiltrates the building materials by **capillary suction** from ground or **rain run-off** and is **stored** in the **pores** of the material.
- **Sorption of water vapor** happens at building surface (molecules of water vapor adhere to the surface of pores in solid building materials).
- **Hygroscopic urban materials** absorbing moisture from the air: *wood, cellulose fibers, soil, vegetation*.
- **Moisture uptake in building materials** is avoided as their thermal conductivity increases and their insulating property decreases.
- Buildings facades are usually strived to be made **impervious to water**.



# Urban canopy: Hydrodynamic interaction

- The *vertical urban facets* receive more rain with stronger wind.
- Only a *little fraction of water collected by facets* is available for **evaporation** as the rest goes to the **sewage system**.
- **Water distribution during the rainfall** is highly variable and depends on:
  - Urban geometry
  - Wind direction
  - Wind magnitude
  - Surface materials
- **Catach ratio  $\eta$**  - ratio of wind-driven precipitation  $R_{wdr}$  reaching a surface over precipitation  $R_h$  with no wind over a horizontal surface



Catch ratio intensity  $\eta$  (-) for wind speed  $U = 5 \text{ m/s}$  and rainfall intensity  $R_h = 1 \text{ mm/h}$



**Thank you  
for your attention**

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